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CHANGING WHAT'S POSSIBLE

ARPA-E: The First Seven Years

A Sampling of Project Outcomes

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Dear Colleagues,

In 2007, the formation of the Advanced Research Project Agency for Energy (ARPA-E) within the Department of Energy was a key recommendation of the "Rising Above the Gathering Storm Report." The formation of the agency was quickly authorized, and ARPA-E began operations upon initial funding at the end of 2009. Now, after seven years of funding transformative R&D activities, ARPA-E has a portfolio of present and alumni project teams that are creating impact by moving their technologies into commercial applications, or significantly advancing the technical understanding in transformative areas of energy science and engineering.

There are many possible statistical measures of the success of the teams supported by ARPA-E. For instance, we can report that since 2009 ARPA-E has provided funding of approximately $1.3 billion through 30 focused programs and three open funding solicitations to more than 475 projects. Of those, 206 are now alumni projects. ARPA-E's project teams cumulatively have published 1,104 peer reviewed technical papers that have been cited 13,518 times, and have been awarded 101 patents. Many teams have successfully leveraged ARPA-E's investment: 36 have started new companies, 60 have continued their technology development with other government support, and 45 have cumulatively raised $1.25 billion in publically reported funding from the private sector to bring their technologies into commercial applications.

Such statistics demonstrate purposeful activity. However, the excitement and potential of these teams' work can only be truly communicated by understanding the challenges they tackled, and what they achieved. This booklet provides a look at selected examples of these achievements. The examples span alumni teams to teams that are just nearing the end of their ARPA-E project contract, with outcomes ranging from new innovations that will bear fruit in the future to innovations that are moving into the energy sector as products today.

We expect that this will be the first of many over-views of project outcomes, and their continuing development after ARPA-E support. Please distribute this to your colleagues as appropriate – we hope to encourage innovative scientists and engineers to continue to engage us with their new ideas, and to consider joining us as Program Directors, Fellows, or Commercialization Advisors.

Sincerely,

Ellen D. Williams

Director of ARPA-E

May 17, 2016

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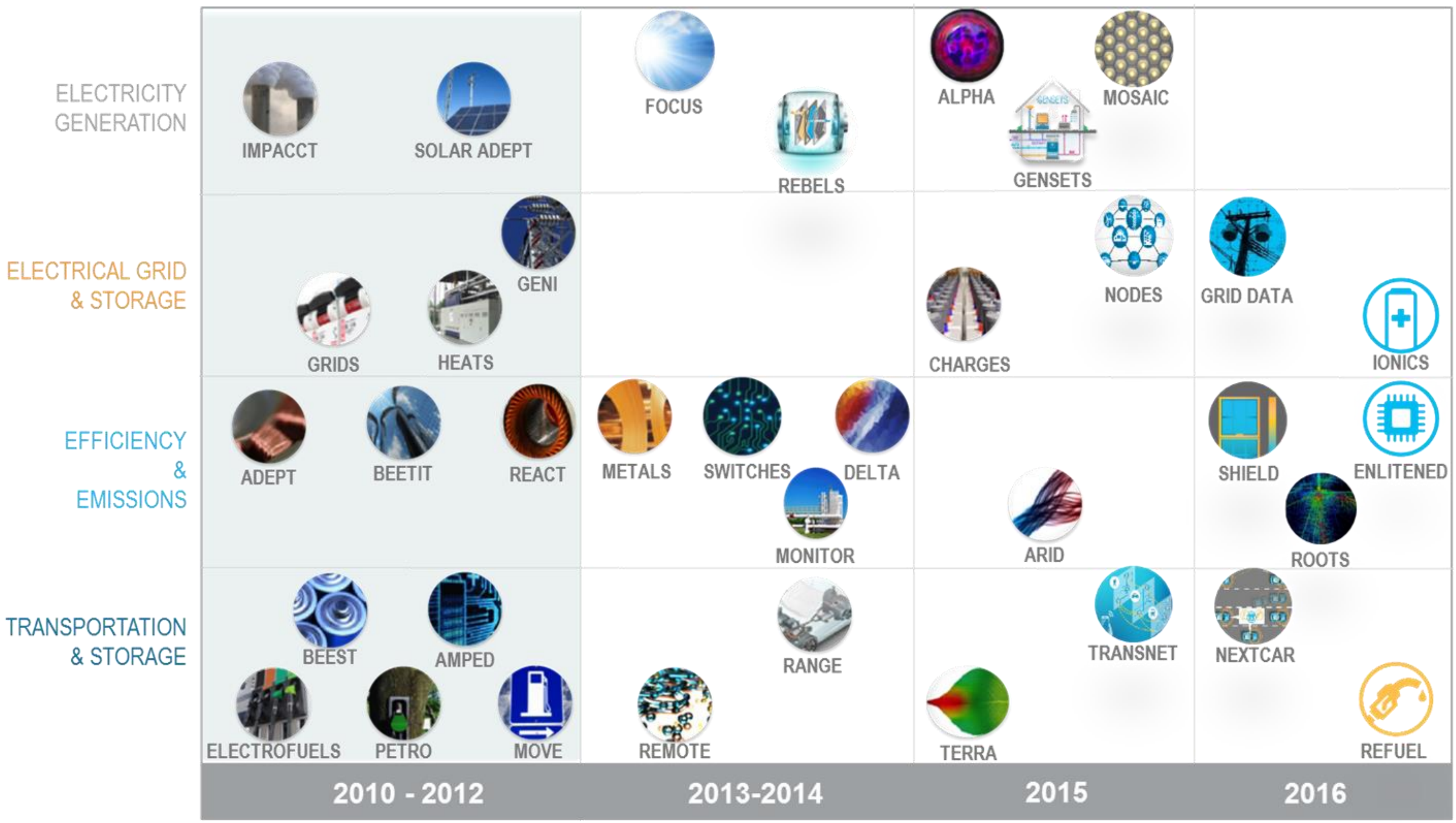
2010-2016 Focused Programs



CHANGING WHAT'S POSSIBLE

DESCRIPTIONS OF ARPA-E'S PROGRAMS

Acronym	Title & Description	Year	Brief Description
ADEPT	Agile Delivery of Electric Power Technology	2010	Power Conversion Efficiency: Wide band-gap semiconductors for high-power, high-current applications
ALPHA	Accelerating Low-Cost Plasma Heating and Assembly	2014	Fusion energy, focused on intermediate density regime, reducing the cost of experimental tests for fusion energy
AMPED	Advanced Management and Protection of Energy Storage Devices	2012	Battery storage, primarily for EV. Addressing efficiency from perspective of the overall battery pack with new approaches to the battery management system. Strong DoD engagement
ARID	Advanced Research in Dry-Cooling	2015	Developing technology to protect Power Plant efficiency under water constraints, more efficient 'dry-cooling'
BEEST	Batteries for Electric Energy Storage in Transportation	2010	All aspects of battery design and materials, supported a large amount of alternative battery chemistry work (supplemented by project awards under OPEN 2009 and 2012)
BEETIT	Building Energy Efficiency Through Innovative Thermodevices	2010	Lower energy approaches to heating, ventilation and air conditioning (HVAC). Some projects funded by DoD
CHARGES	Cycling Hardware to Analyze and Ready Grid-Scale Electricity Storage	2014	Two test sites to allow Grid-scale batteries to be validated under realistic grid operation conditions
DELTA	Delivering Efficient Local Thermal Amenities	2014	Local thermal management for comfort of individuals, goal to reduce overall AC costs by allowing less stringent building-wide AC
ELECTROFUELS	Microorganisms for Liquid Transportation Fuel	2010	Exploratory development of fuel productions by organisms that directly use electric charge as an energy source

Acronym	Title & Description	Year	Brief Description
ENLITENED	Energy-efficient Light-wave integrated Technology Enabling Networks that Enhance Datacenters	2016	Integrated photonic interconnects and novel switching networks for more energy efficient manipulation and movement of data
FOCUS	Full Spectrum Optimized Conversion and Utilization of Sunlight	2014	Solar energy approaches that capture both PV and thermal energy. Approaches include spectrum splitting to different collectors and development of PV cells that can work at the high T of thermal collection
GENI	Green Electricity Network Integration	2011	Electric Power Network - Power flow controllers & software to allow more effective integration of renewables
GENSETS	Generators for Small Electrical and Thermal Systems	2015	Distributed Power Generation - Low-cost, small scale generators for combined heat and power
GRIDS	Grid Scale Rampable Intermittent Dispatchable Storage	2010	Stationary storage, included grid-scale batteries and flow-batteries as well as other approaches such as flywheels. Battery portfolio supplemented through OPEN 2009 and 2012 projects
GRID DATA	Generating Realistic Information for the Development of Distribution and Transmission Algorithms	2015	Development of realistic, open-source models of transmission and distribution grids to support advanced work on optimization and control algorithms
HEATS	High Energy Advanced Thermal Storage	2011	Thermal energy storage, including use of waste heat and storage of heat from Concentrated Solar and from Nuclear Power plant
IMPACCT	Innovative Materials and Process for Advanced Carbon Capture Technologies	2010	Carbon Capture for emissions from coal plants. (supplemented by project awards under OPEN 2009 and 2012)
IONICS	Integration and Optimization of Novel Ion Conducting Solids	2016	Improving the properties of solid ion conductors for batteries, fuel cells, and other electrochemical devices

Acronym	Title & Description	Year	Brief Description
METALS	Modern Electro/Thermochemical Advances in Light Metal Systems	2013	Efficient production and recycling of Al, Mg, Ti – lower cost and energy use to support vehicle light-weighting
MONITOR	Methane Observation Networks with Innovative Technology to Obtain Reductions	2014	Sensing methane and localizing the leak point(s) economically enough for routine use by producers
MOVE	Methane Opportunities for Vehicular Energy Storage tanks	2012	New forms of storage for natural gas that will reduce volume of tanks or allow them to be integrated into the body of the vehicle
MOSAIC	Micro-Scale Optimized Solar-Cell Arrays with Integrated Concentration	2015	Developing compact solar concentration onto high-efficiency cells while also maintain capture of diffuse sunlight
NEXTCAR	Next-Generation Energy Technologies for Connected and Automated On-Road Vehicles	2016	Vehicle and powertrain control technologies to reduce automotive energy use
NODES	Control systems for enhanced use of distributed generation	2015	Developing control algorithms to create effective grid storage through distributed demand response, e.g. water heaters (proposals for this program are now under review)
PETRO	Plants Engineered to Replace Oil Different plant types to produce higher hydrocarbons	2011	Modification of plants to directly produce fuel-ready hydrocarbons
RANGE	Robust Affordable Next -Generation Energy Storage Systems	2013	Battery designs that improve the overall energy density/cost effectiveness of the battery system by using safer materials (e.g. less protective packaging needed)
REACT	Rare Earth Alternatives in Critical Technologies	2011	Materials and motor design approaches that provide options for continued high-efficiency in the event of rare-earth shortages
REBELS	Reliable Electricity Based on Electrochemical Systems	2014	Fuel cells designed for use in distributed power generation (down to residential scale)
REFUEL	Renewable Energy to Fuels Through Utilization of Energy-Dense Liquids	2016	Energy dense liquid fuels from water, and CO_2 and/or N_2 from air powered by renewable electricity

Acronym	Title & Description	Year	Brief Description
REMOTE	Reducing Emissions using Methanotrophic Organisms for Transportation Energy	2013	Biological conversion of methane to fuels
ROOTS	Rhizosphere Observations Optimizing Terrestrial Sequestration	2016	Biofuel plant root phenotyping for improved growth properties and atmospheric carbon sequestration
SHIELD	Single-Pane Highly Insulating Efficient Lucid Designs	2016	Insulating window materials with excellent optical quality which prevent condensation, for cost-effective retrofits or replacements
SOLAR ADEPT	Solar Agile Delivery of Electrical Power Technology	2011	Improved electrical interconnects for integrating Solar Power with the grid. Energy efficiency impact
SWITCHES	Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems	2013	Devices to improve Energy Efficiency for electric motors
TERRA	Transportation Energy Resources from Renewable Agriculture	2015	More rapid development of sustainable biofuels crops. Sensing, robotics, informatics and genetics for advanced phenotyping of energy crops
TRANSNET	Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation	2015	Control architectures and traveler incentives for energy optimization of urban networks

GRID-SCALE BATTERIES

Overview:

Advanced energy storage promises to play a key role in the modernization of our nation's electricity grid. Currently relatively little storage is deployed on the grid. However, low-cost, energy storage can not only enable the integration of more renewable energy on the grid, but it could also improve the grid's operating capabilities and reliability, provide backup power during emergencies and allow deferral of infrastructure investments.

Electrochemical storage (batteries) has the potential to provide flexible grid-scale storage, if enhanced performance and lower cost can be achieved. Since 2009, ARPA-E has invested significantly in R&D of potentially transformative approaches to create new designs, exploit known battery chemistries in new ways, and develop new battery chemistries.

A diversified portfolio of new approaches has resulted, such as ARPA-E's Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) program, which developed battery technologies that can store renewable energy for use at any location on the grid at an investment cost less than $100 per kilowatt-hour. Another ARPA-E program Batteries for Electrical Energy Storage in Transportation (BEEST) developed batteries for electric vehicle (EV) and grid applications and ARPA-E's OPEN funding solicitations have also delivered new and innovative projects focused on producing grid-scale storage options.

The most successful of all of these grid-scale battery projects have demonstrated the potential for low capital cost ($100/kWh installed at the pack level for batteries) and long cycle life, which are two major factors in energy storage cost, with performance characteristics suitable for a range of grid services, including leveling the variability in capacity. The more mature teams have already begun moving new types of storage batteries into the market, where they are providing evidence of the performance and economic benefits needed to incentivize their rapid uptake.

An example of some of the impactful projects in this field can be found below:

- Fluidic (GRIDS) – Enhanced Metal-Air Energy Storage System with Advanced Grid-Interoperable Power Electronics Enabling Scalability and Ultra-Low Cost
- CUNY (GRIDS) – Low-Cost Grid-Scale Electrical Storage Using a Flow-Assisted Rechargeable Zinc-Manganese Dioxide Battery
- Harvard Flow Battery (OPEN 2012) – Small Organic Molecule Based Flow Battery
- 24M (BEEST) – Semi-Solid Rechargeable Power Sources: Flexible, High Performance Storage at Ultralow Cost
- Energy Storage Systems (ESS) (GRIDS SBIR) – 25kW 200kWh Energy Storage System based on All-iron Hybrid Flow Battery
- Primus (GRIDS) – Low-Cost, High Performance Flow Cells
- UTRC (GRIDS) – Transformative Electromechanical Flow Storage System
- Alveo (OPEN 2012) - Open Framework Electrode Batteries for Cost-Effective Stationary Storage

ZINC-AIR GRID ENERGY STORAGE

Updated: February 24, 2016

PROJECT TITLES: Metal-Air Ionic Liquid Batteries; Advanced Grid-Interoperable Power Electronics Enabling Scalability And Ultra-Low Cost	
PROGRAMS: OPEN 2009; Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)	
AWARDS: $5,133,150; $2,993,128	
PROJECT TEAMS: Arizona State University (Lead); Fluidic Energy (Lead)	
PROJECT TERMS: December 2009 – June 2012; October 2010 – March 2013	
PRINCIPAL INVESTIGATOR (PI): Dr. Cody Friesen	

TECHNICAL CHALLENGE

Advanced energy storage promises to play a key role in the modernization of our nation's electricity grid. While relatively little storage is deployed on today's grid, future grid development will likely require energy storage that not only enables the integration of increasing amounts of renewables, but also improves the grid's operating capabilities, enhances reliability, allows deferral of infrastructure investments and provides backup power during emergencies. Electrochemical energy storage, e.g. batteries, provide a significant opportunity to address these needs. Metal-air batteries are particularly attractive because a key component of the battery chemistry, oxygen, is available from the air and doesn't need to be carried in the battery cell, or recharged. However, metal-air batteries are prone to degradation, and historically have not had the ability to discharge and recharge over the large numbers of cycles required to deliver low-cost and extended lifetime energy storage.

TECHNICAL OPPORTUNITY

One major issue for metal-air batteries is that the circulating air carries away evaporating liquids from the electrolyte, degrading battery performance over time. Another issue for the desirable, low-cost Zinc-air (Zn-air) battery is that Zn dendrites form on the anode as the battery is recharged, causing shorting. As a result, commercial Zn-air batteries historically had been limited to disposable (non-rechargeable), low power applications, such as hearing-aid batteries. Advances in materials science offered new opportunities for the design of electrodes and electrolytes that, applied to the Zn-air battery, address the issues that prevent recharging and long lifetime operation.

INNOVATION DEMONSTRATION

With ARPA-E's support, Arizona State University, in partnership with Fluidic Energy, explored innovative approaches to transition nonrechargeable Zn-air battery chemistry into a rechargeable device. They focused on developing a battery design using an electrolyte based on ionic liquids. Ionic liquids are salts that are liquid at the battery operating temperature, delivering ionic conductance while maintaining substantial electrical insulation. The team developed chemistries that have negligible evaporation, are stable in the presence of oxygen, and do not absorb water over the cell operating voltages, and include additives that interact favorably with the Zn and air electrodes. In parallel they experimented with carbon-nano-particle based air electrodes and nanostructured Zn electrodes, the latter including 3-dimensional porous structures that address the problems of formation of Zn dendrites.

Figure 1: Fluidic unit installed in Honduras

As the team demonstrated the ability to cycle using their Zn-air battery designs, Fluidic Energy identified pathways to commercialization. A key issue in optimizing the battery performance was developing stringent control of operating parameters, such as rates of charge/discharge and depth of discharge, at the level of individual cells and modules. With

ARPA-E's support, Fluidic Energy developed a prototype commercializable battery module, including the preliminary development of an advanced control system and integration of continuing improvements in the system of electrodes and electrolyte. Their system targeted kW-level power applications with delivery over 4 to 72 hours, requiring cost and performance competitiveness with traditional back-up power based on diesel generators and/or lead-acid batteries.

PATHWAY TO ECONOMIC IMPACT

In January 2016, Fluidic was recognized as one of the top 100 private firms positioned to solve tomorrow's global clean technology challenges with a 2015 Global Cleantech 100 award.

Additionally, since conclusion of ARPA-E funding to the Fluidic team (in 2013), Fluidic has continued development of its commercial product, and reported the following progress, noting that the company's Zn-air battery and basis for its control system routines resulted directly from the ARPA-E-funded research projects:

As of September 2015, Fluidic has raised approximately $150 million in private sector capital, including a recent equity investment from Caterpillar, Inc., for commercialization of the ARPA-E-funded technologies. Fluidic has established its first markets in cell phone tower backup systems for developing regions, where reliable power delivery is essential. Fluidic's integrated smart controls, which provide remote monitoring, control and diagnostics of the complete energy storage system, have been important to successful commercialization in markets outside of the U.S. The company is now working to transition their technology to broader rural electrification and microgrid applications. As of January 2016, Fluidic has installed more than 50,000 Zn-air battery cells, primarily in South East Asia and Latin America, reducing customer's operating costs while increasing reliability. As of January 2016, Fluidic also reports that the company is entering the rural electrification market, having been selected for 500-islanded renewable microgrids by the Indonesian government.

Fluidic's business model involves fabrication of the high-value components—the anode, cathode and electrolyte—in the U.S. The components are then shipped for pick-and-place assembly near the point of sale.

LONG-TERM IMPACTS

Fluidic's approach of leveraging its developed technology and cost position to deploy in long-duration energy storage markets, often in harsh environmental conditions with demanding operational requirements, has provided access to first markets. The results are beginning to provide the demonstration of effective operations that are needed to open up the long-duration storage market, which Fluidic estimates near term to be more than $25 billion. Such demonstrations are important for supporting entry into the conservative and more cost sensitive power grid systems in developed countries such as the U.S.

In Fluidic's first applications, long-duration energy storage systems demonstrate the use of grid-scale storage for replacement of diesel generators, along with the associated CO_2 emissions. The results are indicative of the types of improvements in reliability of grid services and reduction of greenhouse gas emissions that are possible as battery energy storage continues to improve in cost and performance. As an ancillary benefit, many tons of ionic liquids—chemistries developed under the ARPA-E programs—have been manufactured and deployed by Fluidic Energy; this may be the largest commercial deployment of ionic liquids in the world, and may provide a basis for other commercial developments based on these materials.

INTELLECTUAL PROPERTY

As of February 2016, the Arizona State University and Fluidic Energy team's ARPA-E funded projects have generated 11 invention disclosures to ARPA-E, one pending U.S. Patent and Trademark Office patent application and eight patents issued by the PTO:

Arizona State University "Metal-Air Low Temperature Ionic Liquid Cell". (11/25/2014) US Patent No. 8895197. Washington, DC: U.S. Patent and Trademark Office.

Arizona State University "Metal-Air Cell with Performance Enhancing Additive". (11/10/2015) US Patent No. 9184478. Washington, DC: U.S. Patent and Trademark Office.

Arizona State University "Aluminum-Based Metal-Air Batteries". (1/12/2016) US Patent No. 9236643. Washington, DC: U.S. Patent and Trademark Office.

Fluidic, Inc. "Ionic Liquid Containing Sulfonate Ions". (6/3/2014) US Patent No. 8741491. Washington, DC: U.S. Patent and Trademark Office.

Fluidic, Inc. "Metal-Air Cell Comprising an Electrolyte with a Room Temperature Ionic Liquid and Hygroscopic Additive". (8/19/2014) US Patent No. 8808929. Washington, DC: U.S. Patent and Trademark Office.

Fluidic, Inc. "Degenerate Doping of Metallic Anodes". (5/12/2015) US Patent No. 9029027. Washington, DC: U.S. Patent and Trademark Office.

Fluidic, Inc. "Metal-Air Cell with Ion Exchange Material". (8/25/2015) US Patent No. 9118089. Washington, DC: U.S. Patent and Trademark Office.

Fluidic, Inc. "Methods of Producing Sulfate Salts of Cations from Heteroatomic Compounds and Dialkyl Sulfates and Uses Thereof". (9/29/2015) US Patent No. 9147919. Washington, DC: U.S. Patent and Trademark Office.

LEVERAGING ZINC MANGANESE DIOXIDE FOR STATIONARY ENERGY STORAGE

Updated: February 24, 2016

PROJECT TITLE: Low-Cost Grid-Scale Electrical Storage Using a Flow-Assisted Rechargeable Zinc-Manganese Dioxide Battery
PROGRAM: Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)
AWARD: $3,497,133
PROJECT TEAM: City University of New York (CUNY) Energy Institute
PROJECT TERM: September 2010 – March 2015
PRINCIPAL INVESTIGATOR (PI): Michael Adams

TECHNICAL CHALLENGE

Advanced energy storage promises to play a key role in modernizing our nation's electricity grid to enable the integration of increasing amounts of renewables, improve operating capabilities, enhance reliability, allow deferral of infrastructure investments, and provide backup power during emergencies. To accomplish this, storage systems are needed that can match both the power and energy scale of the electrical grid while minimizing impact on the cost of electric power delivery. Electrochemical energy storage (e.g. batteries) provides significant opportunities to address these needs if lowered cost and increased lifetime can be delivered.

TECHNICAL OPPORTUNITY

The low cost and high-performance opportunity presented by zinc (Zn) and manganese (Mn) electrode materials is attractive for creating batteries for grid storage. Traditional consumer-grade disposable "alkaline" batteries that sell for less than $40/kWh are made of Zn and Mn. These materials are inexpensive, abundant, and non-toxic, but disposable alkaline batteries can only be used once. If they are recharged, the Zn in the battery develops filaments called dendrites that grow haphazardly and disrupt battery performance, while the Mn undergoes irreversible chemical reactions and quickly loses its ability to store energy. However, applying advanced materials approaches to the design of electrodes and electrolytes, coupled with a better understanding of battery management, offers new opportunities to dramatically increase the performance of batteries, reduce their cost, and revisit known materials problems in new and innovative ways.

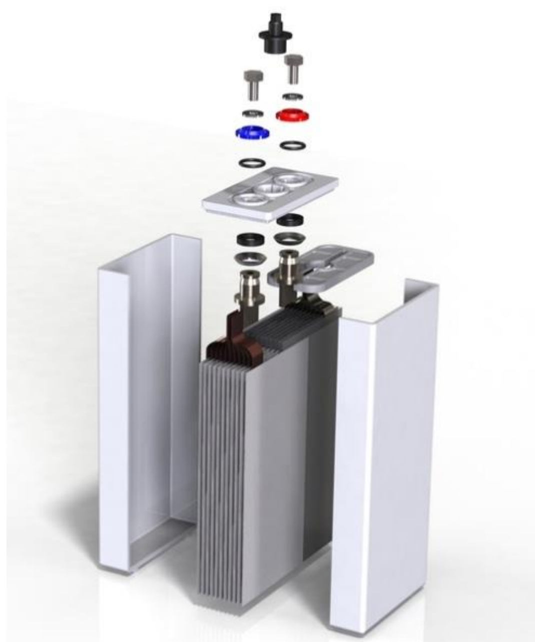


Figure 1. UEP's Zinc Manganese Dioxide prismatic cell

INNOVATION DEMONSTRATION

Prior to the ARPA-E project, researchers at the City University of New York (CUNY) Energy Institute had addressed the issue of dendrite formation by incorporating a "flow-assisted" Zn anode. The CUNY team knew that combining a manganese dioxide (MnO_2) cathode with CUNY's existing Zn anode would result in a very low-cost cell, but CUNY had to address the irreversible chemical changes that result in rapid loss of cell capacity. The CUNY team found specific cycling conditions under which the conventional battery-grade manganese dioxide could be repeatedly charged and discharged. Specifically, the cell's depth of discharge (how much energy was extracted) had to be carefully controlled to a fraction of the material's nominal capacity. MnO_2 was so inexpensive that accessing only part of its capacity did not have a major cost impact on the system. To deliver the controlled depth of discharge, the team—through its award from ARPA-E—developed a sophisticated battery management strategy, as well as optimizing the composition and structure for the positive electrode. Through these innovations, the team demonstrated high cycle life (more than 1,500 cycles) with the new cathode.

To simplify balance of plant and lower system cost, the team also used its ARPA-E award to develop a new approach to the Zn-dendrite problem based on pasted zinc anode. The team improved the performance by modifying the anode microstructure, incorporated novel cell additives, and tested new separator materials. Final cells, incorporating both the improved anode and cathode, cycled over 1,000 times, with projected lifetimes of 5,000 cycles. A chemistry cheap enough to throw away after a single use in consumer electronics, now has the potential to provide a decade or more of service in grid applications.

PATHWAY TO ECONOMIC IMPACT

Members of the CUNY team founded a battery startup, Urban Electric Power (UEP), that has licensed CUNY's Zn-MnO_2 cell technology. Founded in 2013, UEP is supported by private venture and strategic investors. The company reports that it is focused on emerging grid-scale applications, such as energy shifting and renewables integration, as well as in established markets such as uninterruptible power supply (UPS). In the UPS market, the incumbent technology is lead acid batteries, which have moderate energy density, are relatively safe and inexpensive (less than $250/kWh), but also have limited cycle life. UEP reports that batteries resulting from the ARPA-E funded research offer similar energy density and safety, but at a lower cost and with a useful life that is five times as long.

UEP is now (early 2016) offering two grid storage products based on CUNY's technology resulting from the ARPA-E award: a 2 to 50kWh standalone storage system for residential and commercial backup power in developing countries, and a rack-mounted storage unit for use in utility-scale (more than 100kWh) storage applications. UEP reports that the company began shipping small "test units" for potential customers to evaluate in early 2015, and began shipping its standalone storage system for residential and commercial backup power product to customers in late 2015.

LONG-TERM IMPACTS

The rigorous cost requirements of grid-scale batteries have driven re-analysis of old battery chemistries and approaches. The CUNY-UEP collaboration has demonstrated the utility of this approach by developing innovations to make an old chemistry available to provide a decade or more of service in grid applications.

When manufactured in large volumes, UEP believes that its battery packs could have a capital cost of $125/kWh which would deliver storage costs competitive with projections for scaled-up lithium-ion batteries. At this cost level, grid-scale batteries would be well positioned to be economically attractive solutions for a wide range of grid services, setting the stage to enable greatly increased penetration of renewables into the power grid system.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the CUNY team's project has reported 23 invention disclosures to ARPA-E and three U.S. Patent and Trademark Office (PTO) patent applications. The team has also published the scientific underpinnings of this technology in open literature. A list of publications is provided below:

Ingale, N.D.; Gallaway, J.W.; Nyce, M.; Couzis, A.; Banerjee, S. (2015) "Rechargeability and Economic Aspects of Alkaline Zinc-Manganese Dioxide Cells for Electrical Storage and Load Leveling" Journal of Power Sources 276, 7–18.

Gallaway, J.W., Erdonmez, C.K., Zhong, Z., Croft, M., Sviridov, L.A., Sholklapper, T.Z., Turney, D.E., Banerjee, S. and Steingart, D.A. (2014) "Real-time materials evolution visualized within intact cycling *alkaline batteries*" Journal of Materials Chemistry A 2(8) 2757-2764.

DEVELOPING ORGANIC FLOW BATTERIES FOR ENERGY STORAGE

Updated: February 24, 2016

PROJECT TITLE: Small Organic Molecule Based Flow Battery for Grid Storage	
PROGRAM: OPEN 2012	
AWARD: $4,340,035	
PROJECT TEAM: Harvard University (Lead); Sustainable Innovations, LLC	
PROJECT TERM: February 2013 – March 2017	
PRINCIPAL INVESTIGATOR: Mr. Paul Karoff	

TECHNICAL CHALLENGE

Advanced energy storage promises to play a key role in the modernization of our nation's electricity grid. Future grid development will likely require energy storage that not only enables the integration of increasing amounts of renewables, but also improves the grid's operating capabilities, enhances reliability, allows deferral of infrastructure investments, and provides backup power during emergencies. Expanding the benefits of energy storage for the grid will require developing technologies that can be easily sited and can match the power and energy scale of the electrical grid while also minimizing cost. Electrochemical energy storage, e.g. batteries, provides significant opportunities to address these needs. However, wide acceptance of such energy storage solutions for grid services requires technical improvements to deliver greater reliability, cost-effectiveness, and duration of discharge at the required power levels.

TECHNICAL OPPORTUNITY

For grid-scale storage, volume and mass of the storage system is not a primary constraint. As a result flow batteries, which store chemical energy in external tanks, can be used to deliver larger amounts of stored energy at a lower cost per kilowatt hour (kWh). While commercially available flow battery systems have historically been costly, the relaxed volume constraints make it possible to consider chemical components that previously would not have been thought viable. Without the volume constraint, the battery chemicals can be optimized for performance, to drive down the cost of materials and also to reduce the toxicity of the battery components, which otherwise increase manufacturing and operational costs.

INNOVATION DEMONSTRATION

The Harvard team is addressing the challenges of grid storage by designing a flow battery based on inexpensive organic molecules in aqueous (water-based) electrolyte. The team has focused on non-toxic quinone molecules, which can be found in plants such as rhubarb, as an electroactive chemical that can reversibly store energy in a water-based solution at room temperature. The group employed theoretical and organic synthetic methods to evaluate hundreds of thousands of possible quinone-based chemicals that might offer the necessary electrochemical potential, solubility in water, and thermodynamic stability. The first demonstration of these systems, 2,7-anthraquinone disulfonic acid coupled to a bromine solution, has a reduction-oxidation window of 0.8 V. Details of this early, proof of concept battery were published in 2014 (see publications below).

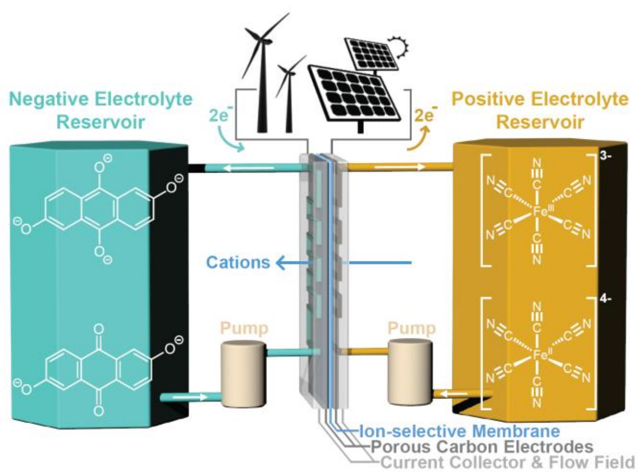


Figure 1. Schematic Diagram of the Harvard Organic Flow Battery

Since these experiments were completed, the group has moved to make their system cheaper and less toxic, and to increase the voltage to 1.2 V. To date, the team has analyzed over one million quinone-based molecules using computer simulation, with thousands of them determined to be promising for storage. Of these, a dozen were selected for synthesis and testing, based upon their expected synthetic feasibility, electrochemical redox potential, aqueous solubility, and chemical stability during operation.

The team has developed a prototype cell design using safer alkaline liquids, no precious metals, and other battery components made of plastic or inexpensive metals with coatings proven to protect against corrosion. The team is advancing this innovative storage concept with goals of improving performance, including power density, cycle life, and round trip efficiency. Their goal is to have a pilot-sale system ready for external testing by the end of the performance period.

PATHWAY TO ECONOMIC IMPACT

Sustainable Innovations, Harvard's commercialization partner, is developing a 3 kW system incorporating Harvard's chemistry for demonstration by the end of the performance period. Sustainable Innovations is currently raising funding to complete commercialization of a low-cost electrochemical platform that will support the launch of a series of products that meet critical market needs. If Harvard's innovative storage concept proves commercially competitive, this technology can be inserted into a low-cost platform to yield a range of quinone based battery systems, with toxicity, cost, and performance features that suit a variety of applications ranging from uninterruptable power supplies through micro-grid back-up, to full grid support. Technoeconomic analysis and customer interest will determine the top candidates resulting from this project.

The relatively non-toxic chemicals used in the battery design are widely used in the textile dye industry. Because these materials are already in commercial production, it is likely that scale-up for the organic battery will be rapid and cost effective.

LONG-TERM IMPACTS

The use of redox-active organics in flow batteries has the potential to significantly drop the cost and toxicity of large scale grid storage batteries. This specific concept of using water-soluble quinones is unprecedented for flow batteries, and now provides a proof-of-concept for low-cost, more environmentally benign alternatives to the accepted chemistries of the past. With continuing development, and scale up to manufacturing in large quantities, redox-active organic battery technology has the potential for a highly competitive evolution of costs.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, Harvard's project has disclosed five inventions to ARPA-E and submitted one patent application to the U.S. Patent and Trademark Office. The Harvard team has received extensive attention from the scientific community and public media. The team has also published the scientific underpinnings of the organic flow battery technology in the literature listed below:

B. Huskinson, M.P. Marshak, C. Suh, S. Er, M.R. Gerhardt, C.J. Galvin, X. Chen, A. Aspuru-Guzik, R.G. Gordon and M.J. Aziz, "A metal-free organic-inorganic aqueous flow battery", *Nature* **505**, 195 (2014).

Kaixiang Lin, Qing Chen, Michael R. Gerhardt, Liuchuan Tong, Sang Bok Kim, Louise Eisenach, Alvaro W. Valle, David Hardee, Roy G. Gordon, Michael J. Aziz, and Michael P. Marshak, Alkaline Quinone Flow Battery, *Science* **349**, 1529 (2015).

Qing Chen, Louise Eisenach, and Michael J. Aziz, Cycling analysis of a quinone-bromide redox flow battery, *Journal of The Electrochemical Society* 163:1, A5057-A5063 (2016).

Suleyman Er, Changwon Suh, Michael Marshak, Alan Aspuru-Guzik, "Computational design of molecules for an all-quinone redox flow battery", *Chemical Sciences*, 6, 2015, 885-893.

Qing Chen, Michael R. Gerhardt, Lauren Hartle and Michael J. Aziz, "A Quinone-Bromide Flow Battery with 1 W/cm^2 Power Density", *Journal of the Electrochemical Society*, Vol 163: 1, 2016, A5010-A5013.

Brian Huskinson, Michael P. Marshak, Michael R. Gerhardt, Michael J. Aziz "Cycling of a Quinone-Bromide Flow Battery for Large Scale Electrochemical Energy Storage", *ECS Transactions*, 61, 2014.

ENHANCED BATTERY CELL PERFORMANCE AND AUTOMATED CELL FABRICATION

ENHANCED BATTERY CELL PERFORMANCE AND AUTOMATED CELL FABRICATION

Updated: February 24, 2016

PROJECT TITLE: Semi-Solid Flow Cells for Automotive and Grid-Level Energy Storage	
PROGRAM: Batteries for Electrical Energy Storage in Transportation (BEEST)	
AWARD: $5,975,331	
PROJECT TEAM: 24 M (Lead); Massachusetts Institute of Technology; Rutgers University	
PROJECT TERM: September 2010 – February 2014	
PRINCIPAL INVESTIGATOR: Dr. Taison Tan	

TECHNICAL CHALLENGE

Batteries are essential components for electric vehicles (EVs) and the systems that store more energy allow for a longer EV driving range. Batteries also have the potential to provide service for the electric power grid, where large-scale energy storage is needed to stabilize the grid and enable increased integration of intermittent renewable power generation. While some batteries, such as lithium (Li)-ion, can be used in vehicles and on the electric grid, a major challenge in both applications is the cost of the battery system, and its associated lifetime.

TECHNICAL OPPORTUNITY

The design of today's cells and the process to manufacture them adds substantial size and cost. To make Li-ion cells today, substantial capital investment is required for specialized coating lines and related facilities for processing the cells. New material formulations provide the opportunity to create modified cell designs that deliver higher performance and can be manufactured less expensively.

INNOVATION DEMONSTRATION

The 24M team proposed to develop a low-cost, high energy density battery for electric vehicles using a new cell design. The team initially investigated a flow battery approach with conventional Li-ion active materials suspended in a slurry (semi-solid mixture). However, within the first year of the project, the 24M team determined that using the slurry to fabricate thick electrodes was a more promising approach to cell design. This allowed them to re-evaluate the need for a flow-cell design for their batteries.

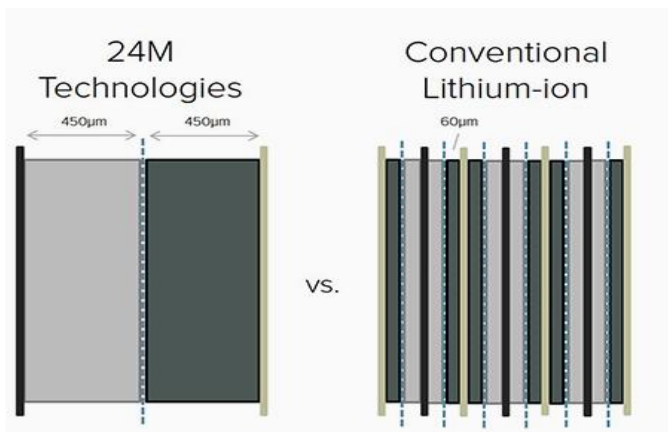


Figure 1. A 24M battery cell is shown on the left side of the diagram, and a stack of conventional lithium ion cells on the right. The 24M cell has two thick (450um) electrodes: a graphite anode (shown in light gray) and a lithium iron phosphate (LFP) cathode (shown in dark gray). The dotted blue line shows a polymer cell separator, and the thin lines on the outside of the cell show the cell current collectors (Cu for the anode, and Al for the cathode). In contrast, six conventional lithium ion cells are shown on the right of the diagram. These cells have much thinner electrodes (60um), but employ separators, and current collectors that are similar to the 24M cell. As a result, more inactive components (separator and current collectors) are used within the same cell volume, adding cost and potentially reducing energy density.

The slurry allows the delivery of the active Li material in the form of a film of closely packed particles in the form of a semi-solid flow. The material delivered covers the current collector completely, and allows thicker films without the cracking and poor adhesion of traditional manufacturing processes. The use of a single thick film greatly simplifies design and fabrication compared with alternating thin films of anode and cathode materials used in traditional cells, as shown in Figure 1.

The new cells have an additional advantage of higher energy density than state-of-the-art large format Li-ion cells because they allow a larger ratio of active material to inactive material.

The 24M team demonstrated a low-cost, scalable fabrication process, in which they mixed the solution, extruded it onto a current collector, and assembled the cell by pressing components together and sealing the cell assembly. The team concluded their ARPA-E project with the successful delivery of a 17Wh cell that used thick electrodes (more than 400 μm) with high loading of active materials (more than 40% vol), cycled at high efficiency (more than 85% roundtrip), and showed reasonable cycle life (more than 1000 cycles) with limited capacity loss. 24M has designed the cell to operate at a continuous charge/discharge rate of C/4, and have also shown good performance in grid duty cycles with sustained power pulses of up to 2C.

PATHWAY TO ECONOMIC IMPACT

Since the conclusion of its ARPA-E project, 24M has continued development of its technology and reported the following progress in commercialization to ARPA-E:

The company has obtained continuing support from venture and strategic investors to continue development of its technology. The research team has developed an automated cell fabrication process, and continued to enhance the performance of its cells, including extending cycle life and increasing active material loading.

Figure 2. Photo of a 40Ah, 300 sq. cm (130Wh) lithium ion pouch cell manufactured by 24M. From the exterior, this looks like a conventional lithium ion cell, but it was manufactured using 24M's unique low-cost process.

By driving down costs and improving performance, 24M's new cell promises to be very competitive compared with the incumbent Li-ion technology and its projected improvements. 24M is targeting its thick-film batteries for providing grid services with intermediate power and energy requirements (~4 hour duration), such as peaker replacement systems, grid asset optimization, and renewable energy time shift. The company is developing strategic partnerships aiming to bring their product into volume production by 2018.

LONG-TERM IMPACTS

The future electric power grid will require energy storage that not only enables the integration of increasing amounts of renewables, but also improves the grid's operating capabilities, enhances reliability, allows deferral of infrastructure investments and provides backup power during emergencies. The advances that 24M has developed in lower-cost manufacturing and battery design offer a significant new pathway to meeting the cost and performance requirements needed for wide-scale adoption of battery systems for grid-scale services, which include battery pack costs of $100/kWh or less with a cycle life of more than 5,000 cycles.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the 24M team's project has generated 11 invention disclosures with ARPA-E, 11 U.S. non-provisional patent applications and four patents issued by the U.S. PTO:

Patents

Semi-Solid Electrodes Having High Rate Capability U.S. Patent No. 8,993,159; issued March 31, 2015

Electrochemical Cells and Methods of Manufacturing the Same; U.S. Patent No. 9,178,200; issued November 3, 2015

Semi-Solid Electrodes Having High Rate Capability U.S. Patent No. 9,184,464; issued November 10, 2015

Stationary Semi-Solid Battery Module and Method of Manufacture; U.S. Patent No. 9,203,092; issued December 1, 2015

The 24M team has also published the scientific underpinnings of the technology in the open literature. The publications are provided below:

Publications

Bae, et. al. (2013). Design of Battery Electrodes with Dual-Scale Porosity to Minimize Tortuosity and Maximize Performance" *Advanced Materials*, volume 25(9), p. 1254–1258.

Brunini, et. al. (2012). Modeling the hydrodynamic and electrochemical efficiency of semi-solid flow batteries. *Electrochimica Acta.*, volume 69, p. 301-307.

Duduta, M., et. al. (2011). Semi-Solid Lithium Rechargeable Flow Battery. *Advanced Energy Materials*, volume 1(4, July) p. 511–516.

Smith, et. al. (2014). Maximizing energetic efficiency in flow batteries utilizing non-Newtonian fluids" *Journal of The Electrochemical Society*, volume 161(4), p. A486-A496.

NEW IRON BATTERY DESIGN FOR FLOW BATTERIES

Updated: February 24, 2016

PROJECT TITLE: 10kW 80kWh Energy Storage System Based on All-Iron Hybrid Flow Battery	
PROGRAM: Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) Small Business Innovation Research (SBIR)	
AWARD: $2.25 million	
PROJECT TEAM: Energy Storage Systems (ESS Tech, Inc.)	
PROJECT TERM: October 2012–December 2016	
PRINCIPAL INVESTIGATOR (PI): Dr. Julia Song	

TECHNICAL CHALLENGE

Advanced energy storage promises to play a key role in the modernization of our nation's electricity grid. While relatively little storage is deployed on today's grid, future grid development will likely require energy storage that not only enables the integration of increasing amounts of renewables, but also improves the grid's operating capabilities, enhances reliability, allows deferral of infrastructure investments and provides backup power during emergencies. To expand the benefits of energy storage for the grid, storage systems are required that can match both the power and energy scale of the electrical grid while minimizing impact on the cost of electric power delivery. Electrochemical energy storage, e.g. batteries, provides significant opportunities to address these needs, if lowered cost and increased lifetime can be delivered.

TECHNICAL OPPORTUNITY

Redox flow batteries are attractive for grid storage because the amount of stored energy can be scaled independently of the battery's power level. This is because the energy is stored in liquid electrolytes that are pumped from storage tanks through a cell stack (the active part of the battery, including the electrodes) during charging and discharging. Historically, flow cells have been limited in power delivery because energy was not efficiently transferred from the liquids to the battery electrodes. Issues of stability in cycling the electrolytes have also limited the choice of the chemical used in fuel cells, resulting in high costs. Improved understanding of fluid dynamics and new approaches to managing electrolytes offer new opportunities to dramatically increase the performance of flow batteries, as well as bring down their cost.

INNOVATION DEMONSTRATION

Energy Storage Systems (ESS) initially focused on improving energy density by adapting the understanding of chemical flow to the electrodes from their experience with fuel cells. The company developed a high-power cell and a compact stack design based on vanadium chemistry. ESS then evaluated other chemistries to address the high cost of the vanadium-carrying electrolytes, which was a large fraction of overall system cost. Early academic literature on the iron-flow battery (IFB) indicated a potential low-cost approach using abundant iron as the active material, but state-of-the-art power densities were low (50mW/cm2), so there was a clear opportunity to

Figure 1. Photo of ESS battery stacks

leverage ESS' high-power cell design in conjunction with the iron chemistry.

ESS adapted its cell and stack design to use iron chloride ($FeCl_2$) electrolytes that cost less than 1/10 of the vanadium-carrying electrolytes. The resulting high-power cell design has demonstrated a four-fold power density increase over existing iron flow battery technologies.

In addition to the low power density of traditional IFBs, ESS also had to address the problem of cycle life. When ESS began its project, state-of-the-art IFBs exhibited round trip efficiency of roughly 50% and life of less than 100 cycles. Chemical side reactions limited the cycle life by altering the pH of the electrolyte and causing precipitation of active species. The ESS team developed an effective chemical rebalancing system that ensures the IFB can cycle over extended periods. After incorporation of its rebalancing system, ESS demonstrated single-cell cycle life of more than 2,500 cycles without measurable degradation, and AC energy efficiency of 70% in a scaled-up 10kW/75kWh IFB.

PATHWAY TO ECONOMIC IMPACT

ESS has delivered a package targeted to be very competitive with incumbent battery systems and continues to focus on further lowering its system costs with emphasis on low-cost cell components, including membrane and electrodes.

ESS' first markets for the product are customer-owned systems (less than 100kW in size) coupled with renewables for firming and load management. To increase customer benefits, ESS has developed a battery management system in which end-users have a way to harness their local electricity rates structures to their economic advantage. ESS' first customers include the U.S. Army Corps of Engineers and Stone Edge Farms, a winery in Napa, CA. In addition, ESS has approximately $1 million in firm orders for delivery in the first half of 2016. As ESS moves into higher-volume production, the company is also seeking to drive cost out of its system through manufacturing improvements.

ESS announced in October of 2015 that the company had closed a $3.2 million Series A round that was led by Pangaea Ventures. This funding will be used for working capital and to scale up manufacturing to meet initial system orders.

LONG-TERM IMPACTS

The successful application of high-power flow-cell designs, and the development of approaches to address chemical imbalances and incorporate lower-cost materials, remove the two most serious barriers to commercial applications of flow batteries for grid storage. ESS' results help to position flow cells to move into the larger applications in the grid needed to create significantly expanded integration of intermittent renewable power sources.

With increasing production scale, continuing development of lower-cost cell components and the potential for significant increases in cycle life, ESS is positioned to be very competitive in the rapidly developing grid storage market, with the potential to deliver storage costs that minimize the impact on the levelized cost of electricity.

INTELLECTUAL PROPERTY

As of February 2016, the ESS project has resulted in seven subject invention disclosures and six U.S. Patent and Trademark Office patent applications.

LONG-LIFE ENERGY STORAGE SYSTEMS CREATE A MORE EFFECTIVE AND RELIABLE ELECTRIC GRID

Updated: February 24, 2016

PROJECT TITLE: Low-Cost, High-Performance 50-Year Electrodes	
PROGRAM: Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)	
AWARD: $1,999,999	
PROJECT TEAM: Primus Power (Lead)	
PROJECT TERM: September 2010 – December 2012	
PRINCIPAL INVESTIGATOR (PI): Mr. Rick Winter	

TECHNICAL CHALLENGE

Advanced energy storage promises to play a key role in the modernization of our nation's electricity grid. While relatively little storage is deployed on today's grid, future grid development will likely require energy storage that not only enables the integration of increasing amounts of renewables, but also improves the grid's operating capabilities, enhances reliability, allows deferral of infrastructure investments, and provides backup power during emergencies. Expanding the benefits of energy storage for the grid requires energy systems that can match both the power and energy scale of the electrical grid while minimizing impact on the cost of electric power delivery. Electrochemical energy storage, e.g. batteries, provides significant opportunities to address these needs, if lowered cost and increased lifetime can be delivered.

TECHNICAL OPPORTUNITY

Redox Flow Batteries (RFB) are attractive for grid storage because the amount of stored energy can be scaled independently of the battery's power level. This is because the energy is stored in liquid electrolytes that are pumped from storage tanks through a cell stack (the active part of the battery, including the electrodes) during charging and discharging. Historically, flow cells have been limited in power delivery because energy was not efficiently transferred from the liquids to the battery electrodes. Improved understanding of fluid dynamics and advanced materials approaches to design of electrodes and electrolytes offer new opportunities to dramatically increase the performance of flow batteries, as well as bring down their cost.

Figure 1. Primus Power's fully self-contained, hermetically sealed flow battery

INNOVATION DEMONSTRATION

One of the most costly components in a flow battery is the electrode, where the electrochemical reactions actually occur. Primus focused on the development of a long-life electrode that successfully extends the stack lifetime and reduces system cost. The Primus team replaced the standard carbon-base for the electrodes with a new structure based on a metal substrate and structured mixed-metal catalyst, thus improving resiliency and electrical conductivity, and enhancing the surface area to support the catalysts that interact with the electrolyte. The team drew on mature technologies and processes from the chlor-alkali, filter media, and electroplating industries and adapted them to the specialized needs of a flow cell based on Zinc (Zn)-halogen chemistry.

The team successfully developed and integrated an electrode into the advanced battery stack. In initial tests with a Zn-Chlorine (Cl) chemistry there was a high level of corrosion. Primus developed alternative electrolytes to find a balance that minimized corrosion, and ultimately optimized Primus' flow cell for Zn-Bromine (Br) chemistry. Primus ultimately developed a highly durable advanced metal electrode that significantly extends the stack lifetime.

Throughout the development of this non-traditional flow battery, Primus focused on increasing operating current density to generate more power from the stack, and developed a unique hybrid flow design in the cell which improved the performance and reduced the stack cost per watt of power delivered. Under its ARPA-E award, Primus' resulting system delivered five times higher stack power than previous commercial Zn-Br batteries and cycle life that was eight times longer. Then-current state-of-the-art densities were 15-30 mA/cm^2 for commercial Zn-Br systems, however Primus' final stack operated at 150 mA/cm2 in the ARPA-E project. Additionally, the lifetime of the Primus system substantially exceeded state-of-the-art cycles of 2,000 cycles over a typical stack lifetime, with higher than 17,000 cycles possible if degradation of components (including electrodes) is controlled.

PATHWAY TO ECONOMIC IMPACT

Since the conclusion of its ARPA-E project, Primus Power has continued development of its product and reported the following progress in commercialization to ARPA-E, noting that the electrode, flow battery, battery systems addressed in the text below resulted directly from Primus' ARPA-E research project:

Since Primus Power was incorporated in 2009 (shortly before it received its ARPA-E award) the company has raised over $60 million in private investor funding from Anglo American Platinum, Chrysalix Energy Venture Capital, DBL Partners, I2BF Investors, Kleiner Perkins Caufield & Byers and Russia-Kazakhstan Nanotechnology Fund (RKNF). The successful development of a long-life electrode for stationary storage systems has resulted in systems competitive with today's market-standard Lead (Pb)-Acid and Lithium (Li)-ion batteries. Primus Power has flow batteries available commercially in a modular 25 kW • 125 kWh system. Primus is developing market acceptance for its products through participation in demonstration projects, and has begun product sales.

A Primus battery is an integral part of a microgrid being tested at the Marine Corps Air Station (MCAS) in Miramar, California. The MCAS microgrid includes a 230 kW solar photovoltaic array, the Primus battery, and an energy management system. Primus reports that the system has met the Marine Corp's two major requirements: reduce demand charges imposed by local utility when electricity is consumed at peak times, and provide power to critical systems when grid power is unavailable.

Primus has delivered ~20 battery systems and in September 2015 announced an order for 1,250 batteries from a major Asian utility with 21,000 MW of generating capacity. In October 2015, Primus delivered a "behind the meter" system to an industrial facility in Southern California. ICL—the Israeli specialty minerals giant—is using a single 20 kW battery to better manage electricity costs at the ICL manufacturing facility in Rancho Cucamonga.

In early 2016, Primus shipped its first international system. Samruk-Energy, the principal electricity provider in the Republic of Kazakhstan, will use a Primus battery system at a 2 MW solar farm in Kapchagay. Future battery systems to Samruk-Energy will be located at a 45 MW wind farm in Yermentau, outside of Kazakhstan's capital Astana. Kazakhstan has strongly embraced wind and solar and has set aggressive renewable energy goals: 30 percent by 2030 and 50 percent by 2050. These initial commercial shipments provide the opportunity of learning curves for reduction in cost, and further product development to meet customer needs. Primus Power is targeting a wide range of storage applications for U.S. and international microgrid, utility, military, commercial, and industrial customers.

LONG-TERM IMPACTS

In the past 5 years, the commercial development of batteries for grid-scale energy storage has become increasingly competitive. Plans to scale up manufacturing of Li-ion batteries to above 10 GWh/yr may decrease their costs by a further 30% or more and the batteries may deliver life cycles of up to 7,000. Flow cells in general have the potential to result in significantly greater cost reduction with production at scale, as a result potential for much larger life cycle numbers, and the independent scaling of energy and power.

Primus Power's electrode design technology developed under its ARPA-E award has demonstrated the competitive performance and lowered storage costs possible with flow batteries. Primus Power's flow battery system has demonstrated potential to deliver very long lifetimes, and to cost less when manufactured in high volumes than the projections for Li-ion batteries at scale. The demonstration of such new technologies in challenging commercial applications is an essential step in incentivizing growing use of battery storage for modernizing the electric power grid.

INTELLECTUAL PROPERTY

As of February 2016, this project has resulted in three subject invention disclosures, four patent applications, and one issued patent from the U.S. Patent and Trademark Office.

La O', GJ. "Electrolyte Flow Configuration for a Metal Halogen Flow Battery". (2012) *US Patent No. 8,137,831*. Washington, DC: U.S. Patent and Trademark Office.

CREATING LONG-LIFE ENERGY STORAGE SYSTEMS

Updated: February 24, 2016

PROJECT TITLE: Transformative Electrochemical Flow Storage System (TEFSS)	
PROGRAM: Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)	
AWARD: $3,599,894	
PROJECT TEAM: United Technologies Research Center (URTC) (Lead); 3M Corporation; University of Texas, Austin	
PROJECT TERM: September 2010 – September 2013	
PRINCIPAL INVESTIGATOR (PI): Mr. Michael Perry	

TECHNICAL CHALLENGE

Advanced energy storage promises to play a key role in the modernization of our nation's electricity grid. While relatively little storage is deployed on today's grid, future grid development will likely require energy storage that not only enables the integration of increasing amounts of renewables, but also improves the grid's operating capabilities, enhances reliability, allows deferral of infrastructure investments, and provides backup power during emergencies. When the Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) program was deployed in 2010, so few grid storage systems were installed that cost data was often sparse and highly variable. However, the Electric Power Research Institute (EPRI) reported in 2010 that costs of all-vanadium redox flow battery systems (200kW-1.2MW, 3.5 hour duration) were $910-$1,250/kWh, while Lithium (Li)-ion battery systems with similar duration cost $950-$1,900. To expand the benefits of energy storage for the grid, the GRIDS program estimated that ten-fold reduction in cost below the 2010 levels was required.

TECHNICAL OPPORTUNITY

Redox flow batteries are particularly attractive for grid storage because the amount of stored energy, important for large capacity applications, can be scaled independently of the battery's power level. Flow batteries store energy in liquid electrolytes that are pumped from storage tanks through a cell stack during charging and discharging. Maintaining electrolyte stability over many cycles has been a barrier in flow-cell development, with all-vanadium flow batteries proving one of the most effective solutions. However, vanadium flow batteries have required expensive ion-exchange membrane, carbon electrodes, and bipolar plates that can account for as much as 40% of the total system cost. The understanding of fluid flow in electrochemical cells has been significantly improved by extensive research in fuel cells, providing new opportunities to improve design and lower costs for flow-cell batteries.

INNOVATION DEMONSTRATION

United Technologies Research Center (UTRC) focused on designing a high-power cell that extracted more power without increasing the scale of the expensive components, ultimately reducing the capital cost of the stack per watt of power generated. Key cell innovations were borrowed heavily from the polymer electrolyte membrane (PEM) fuel cell design and included the use of interdigitated flow field for efficient reactant delivery, and incorporation of thin electrodes for improved mass transfer and reaction kinetics.

Figure 1: Vionx Energy's Vanadium Redox Flow Battery System

UTRC's high-power flow battery, which delivered peak power of nearly 1,400mW/cm^2, a tenfold increase over state-of-the-art flow cells at the time, proved to be a key innovation. UTRC integrated its high-power cell into a 20kW flow battery system and demonstrated high energy efficiency over 100 cycles with no detectable degradation. While UTRC's basic high-power cell design was developed utilizing all-vanadium systems, it can be applied in any flow battery system that uses liquid reactants and produces liquid reaction products.

Following UTRC's successful increase in power density of the cell stack, UTRC addressed another key issue for stability and cost: membrane optimization. The original project used conventional, off-the-shelf ion-exchange membranes, which had an inherent tradeoff: thinner membranes allowed for less ionic resistance, but also allowed for greater crossover of reactant species, which reduced cell efficiency. UTRC worked with 3M to fabricate a membrane that maintained high-proton conductivity but offered low permeability to vanadium. The resulting membrane permitted a doubling in operating current density of UTRC cells, further increasing stack power density and decreasing stack cost.

PATHWAY TO ECONOMIC IMPACT

UTRC's successful development of a high-power stack enabled a 2 times greater reduction in cost (which makes it competitive with today's lithium-ion-based storage systems) while also offering a lifetime of greater than 7,500 cycles.

As of November 2015, UTRC licensed its high-power all-vanadium system to Vionx Energy. The company has containerized 65kW/400kWh energy storage units for sale. Vionx deployed its first unit to the U.S. Army at Fort Devens, Massachusetts in 2015. Vionx is collecting data based on 160 kW to 500 kW systems in the field and will use this data to determine future market opportunities.

Vionx has raised tens of millions of dollars to further develop and deploy the all-vanadium battery technology developed by UTRC in its ARPA-E project. This funding comes from an investor group led by Starwood Energy and Vantage Point Capital Partners.

LONG-TERM IMPACTS

UTRC's development of a high-power all-vanadium battery is a significant demonstration in the ability to advance energy storage to the lower costs and higher performance needed both for first market applications in micro-grids, and for longer term, larger scale applications. These advances in battery technology provide a pathway to reduce cost and to demonstrate and quantify their value in providing grid services. With increasing production scale, continuing development of lower-cost cell components and eletrolyte formulas, UTRC is positioned to remain competitive in the rapidly developing grid storage market.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the UTRC team's project has resulted in four subject invention disclosures and three U.S. patent applications. The UTRC team has also published eight scientific papers about flow cell batteries. A list of the publications is provided below:

Darling, R. and Perry, M. (2014). The Influence of Electrode and Channel Configurations on Flow Battery Performance, *Journal of the Electrochemical Society*, volume 161(9), p.A1381.

Darling R., and Perry M., (2013). Half-Cell, Steady-State Flow-Battery Experiments. *ECS Transactions*, volume 53(7), p.31.

Darling, R., Weber, A., Tucker, M. and Perry, M. (2016). The Influence of Electric Field on Crossover in Redox-Flow Batteries, *Journal of the Electrochemical Society*, volume 163(1), p.5014.

Li, W., Zaffou, R., Shovlin, C., She, Y., and Perry, M., (2013). Vanadium Redox-Flow-Battery Electrolyte Preparation with Reducing Agents. *ECS Transactions*, volume 53(7), p.93.

Perry, M., Darling R., and Zaffou R., (2013). High Power Density Redox Flow Battery Cells. *ECS Transactions*, volume 53(7) p.7.

Perry, M. and Weber, A. (2016). Advanced Redox-Flow Batteries: A Perspective, *Journal of the Electrochemical Society*, volume 163(1), p.5064.

Xie, W., Darling, R., and Perry, M. (2106). Processing and Pretreatment Effects on Vanadium Transport in Nafion Membranes, *Journal of the Electrochemical Society*, volume 163(1), p.5084.

Zaffou, R., Li, W., and Perry M., (2012). Vanadium Redox Flow Batteries for Electrical Energy Storage: Challenges and Opportunities. *Polymers for Energy Storage and Delivery: Polyelectrolytes for Batteries and Fuel Cells, American Chemical Society Symposia Series,* volume 1096.

OPEN FRAMEWORK MATERIALS ENABLE LOW-COST, LONG-LIFE BATTERIES

Updated: May 31, 2016

PROJECT TITLE: Prussian Blue Open Framework Electrode Batteries	
PROGRAM: OPEN 2012	
AWARD: $4,599,935	
PROJECT TEAM: Alveo Energy	
PROJECT TERM: February 2013 to March 2016	
PRINCIPAL INVESTIGATOR (PI): Dr. Colin Wessells	

TECHNICAL CHALLENGE

Advanced energy storage promises to play a key role in the modernization of our nation's electricity grid by enabling the integration of increasing amounts of renewables, improving the grid's operating capabilities, enhancing reliability, allowing deferral of infrastructure investments and providing backup power during emergencies. The primary barrier to widespread adoption of electrical energy storage is lifecycle cost. Overcoming this barrier requires a combination of capital costs that are significantly lower than incumbent Lithium-ion (Li-ion) and extremely long cycle life.

TECHNICAL OPPORTUNITY

An important class of electrochemical energy storage materials – intercalation compounds – has many positive attributes and widespread adoption, but also has limited cycle life because mechanical expansion/contraction during charge/discharge ultimately leads to material failure. Just prior to the award of this project, it was established that open framework crystalline materials, which readily transport ions, such as Prussian Blue, do not suffer this failure mode and may therefore provide both long cycle life and high power.[1] This is one of the few significant new energy storage materials advances in the last fifty years. This new novel class of materials has presented several barriers to implementation, such as aqueous instability, lack of matching anode material, and cost effective production of battery quality material. Solving these barriers was required in order to provide a path towards a commercially significant and sustainable storage solution.

INNOVATION DEMONSTRATION

Alveo's primary goal was to develop a practical, low-cost, high-performance battery based on chemical analogues of Prussian Blue dye. The cell performance goals included power capability up to 20C rate, projected cycle life >10,000 cycles, and projected calendar life >10 years.

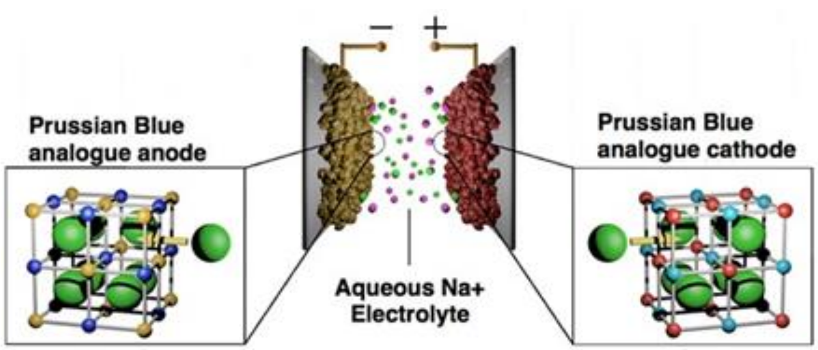


Figure 1. New Na+ battery chemistry based on Prussian Blue analogue anodes and cathodes in aqueous Na+ electrodes. The electrodes have near-zero strain during cycling.

Alveo began with a development of an open framework cathode material based on Prussian Blue dye and developed an anode based on a similar crystal structure. The anode-cathode combination was designed and demonstrated to have an average cell voltage of 1.6 V, high enough for

[1] Wessells, C.D., et al. Nat. Commun. 2:550 (2011).

practical commercial packs and systems. The company implemented this couple in a substantially aqueous cell, to provide intrinsic safety and thus reduce the balance of system costs. In doing so, Alveo was awarded five patents (listed below) on the composition of matter of its electrodes and electrolyte.

Alveo carried out extensive charge/discharge testing of the system components at 20C rate, and demonstrated that the cells have a high power capability equivalent to >1,000 W/L for large form factor production cells—higher than present commercial Li-ion power cells at a fraction of the cost. The company also developed a novel nonflammable aqueous-organic electrolyte, solving the problem of active material dissolution and instability in purely aqueous electrolytes, in order to achieve industry leading calendar and cycle life. Furthermore, they demonstrated that an extremely long cell lifetime (over 30,000 cycles) at full charge/discharge is possible, based on over 7 months and 10,000 measured cycles at 100% depth of discharge.

After successfully demonstrating cell chemistry and design, Alveo scaled up active material synthesis and commercially viable manufacturing processes based on roll-to-roll electrode processing compatible with existing manufacturing lines, with a focus on low capital cost. The team has built and tested demonstration batteries of up to 2Ah capacity for third-party testing, including the Unitersity of California, San Diego Cycling Hardware to Analyze and Ready Grid-Scale Electricity Storage (CHARGES) program, and for customer engagement. Alveo has demonstrated a useful combination of attributes, extremely long cycle life (projecting to >30,000 cycles), high power, low capital cost and fundamental safety (substantially aqueous). The trade-off for this is a moderate energy density (50 Wh/L) which makes this technology most suitable for grid-scale energy storage and back-up power.

PATHWAY TO ECONOMIC IMPACT

Alveo was established primarily on the basis of PhD work[2] of one of the co-founders – Dr. Colin Wessells – conducted while he attended Stanford Univeristy. Khosla Ventures provided initial funding. In March 2016, Alveo closed a B round with Prelude Ventures as the lead and contributions from Khosla Ventures, NanoDimension and Fluxus Ventures.

The company is still in the development phase for its first commercial cells and has potential customers with high interest in back-up power; other markets in which the break-through low cost cycle life makes the product compelling are nearly all renewables integration scenarios and start/stop for electrified transportation.

LONG-TERM IMPACTS

The successful implementation of open framework active materials into a battery with breakthrough life cycle will potentially impact both the technical community and the battery storage markets. In the technical community, the results may lead to new directions of investigation in materials science for energy storage materials, with potential for further improvements in storage properties. For instance, it may potentially drive forward the rapidly growing field of sodium-ion batteries, which includes several promising chemistries that could achieve a much lower cost/energy floor than incumbent technologies such as Li-ion and lead acid.

For markets, such breakthroughs in low cost cycle life open realistic opportunities for battery storage to improve grid stability and enable expanded grid integration of renewables. The anticipated life cycle costs would be sufficient to enable renewables to compete with existing fossil fuel base load generation, provided that related system level cost reductions continue – for example in power conversion.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of March 2016, the Alveo project has resulted in 14 U.S. Patent and Trademark Office (PTO) patent applications and 5 patents issued by the U.S. PTO. The team has also collaborated with researchers at Lawrence Berkeley Lab and NYU to explore the scientific underpinnings of this technology, and their first publications in the scientific literature are expected in mid-2016.

"*Stabilization of battery electrodes*," (9/8/2015) Patent No 9,130,234, Washington, DC: U.S. Patent and Trademark Office.

[2] Wessells, C.D. *New Materials Systems for Aqueous Batteries*. Diss. Stanford University, 2012.

"*Stabilization of battery electrodes using prussian blue analogue coatings*," (9/1/2015), Patent No 9,123,966, Washington, DC: U.S. Patent and Trademark Office.

"*Homometallic cyanide-containing inorganic polymers and related compounds*," (8/4/2015), Patent No 9,099,740, Washington, DC: U.S. Patent and Trademark Office.

"*Cosolvent electrolytes for electrochemical devices*," (3/15/16) Patent No 9,287,589, Washington, DC: U.S. Patent and Trademark Office.

"*Surface-modified cyanide-based transition metal compounds*," (3/29/2016), Patent No 9,299,981, Washington, DC: U.S. Patent and Trademark Office.

TRANSPORTATION – DIRECT AND ENABLING TECHNOLOGIES

Overview:

ARPA-E has invested in vehicle technologies and fuels that offer alternatives to vehicles powered by petroleum fuels using internal combustion engines. The overarching strategy is to provide a diverse set of transportation technologies that help to reduce both energy consumption and net carbon dioxide emissions.

Electric Vehicles (EVs) represent one such alternative transportation technology but the adoption of EVs has been slow, in part because current battery technology limits driving range and is too expensive. ARPA-E has invested in two different areas to address these challenges: (1) using advanced sensor technology and control systems to get more out of the current generation of lithium ion batteries, which are now designed to be one and a quarter to two times larger than actually needed to power the EV (the "Advanced Management and Protection of Energy Storage Devices" or AMPED program) and (2) changing the chemical composition of batteries to provide higher energy at low cost (through several programs, including Small Business Innovation Research (SBIR)).

Natural gas vehicles (NGV) provide a significant opportunity to increase U.S. energy security, enabled by the substantial increases in U.S. natural gas reserves and annual production over the past ten years. However, current NGVs, which burn natural gas in internal combustion engines and produce less carbon dioxide emissions than petroleum powered engines, are limited to large trucks and buses because the lower energy density of compressed natural gas requires bulky and expensive onboard tanks. The ARPA-E "Methane Opportunities for Vehicular Energy" or MOVE program developed innovative technologies for inexpensively compressing natural gas and storing it in novel, space-optimizing tank designs that enable natural gas powered light duty and passenger vehicles.

Biofuels offer renewable alternatives to petroleum-based fuels that reduce net greenhouse gas (GHG) emissions to nearly zero. Today's vision for cost-competitive domestically produced biofuels are hampered by a number of issues, one of which is that today's fuel-rich crops do not provide enough of a step up (based on energy yield per unit area) to be a cost-effective alternative for production of transportation fuel at scale. The "Plants Engineered to Replace Oil" or PETRO program aims to redirect the processes for energy and carbon dioxide capture in plants toward fuel production. This would create dedicated energy crops that serve as a domestic alternative to petroleum-based fuels and deliver more energy per acre with less processing prior to the pump. Other projects from OPEN funding solicitations have been cohorted with PETRO to offer additional approaches to more energy-rich biofeedstocks.

The following examples provide a good sampling of the breadth of ARPA-E's investments in direct and enabling clean transportation technology:

- Ford (AMPED) – High Precision Life Testing of Automotive Batteries and Grid Storage Batteries
- PARC (AMPED) – Smart Embedded Network of Sensors with Optical Readout
- Sila (SBIR) – Doubling the Energy Density Anodes of Lithium-ion Batteries for Transportation
- FastCap (OPEN 2009) – Open Low-Cost, High Energy and Power Density, Nanotube-Enhanced Ultracapacitors
- REL (MOVE) – Fully and Intricately Conformable, Single-Piece, Mass-Manufacturable High-Pressure Gas Storage Tanks
- Onboard Dynamics (MOVE) – Vehicle-integrated Natural Gas Compressor
- Plant Sensory Systems (OPEN 2012) – Development of High-Output, Low-Input Energy Beets
- University of Florida – Commercial Production of Terpene Biofuels in Pine

DEVELOPING A HIGH PRECISION BATTERY TESTING DEVICE

Updated: February 24, 2016

PROJECT TITLE: High-Precision Tester for Automotive and Stationary Batteries	
PROGRAM: Advanced Management and Protection of Energy Storage Devices (AMPED)	
AWARD: $3,128,000	
PROJECT TEAM: Ford Motor Company (Lead); Arbin Instruments; Sandia National Laboratory; Montana Tech University	
PROJECT TERM: January 2013 – March 2016	
PRINCIPAL INVESTIGATOR (PI): Dr. Alvaro Masias	

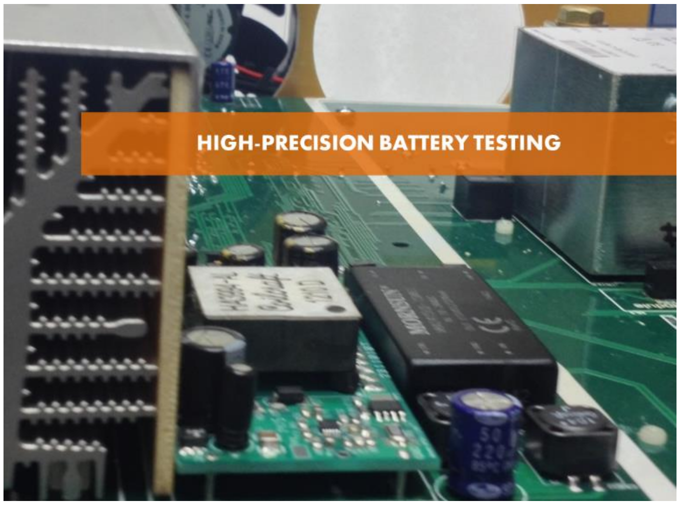
TECHNICAL CHALLENGE

To meet the performance, lifetime, and cost requirements for electric vehicles and grid-scale energy storage, significant continuing advances in battery technology are required. One barrier to progress is the length of time required to test the properties of a new battery design. Standard lifetime prediction methods with state-of-the-art testers typically require 10-30% of the battery's intended life to be tested. While these turn-around times are acceptable for batteries for consumer electronics (with 1 year required lifetimes), they are too slow for automotive and stationary energy storage applications (with 10-30 year required lifetimes). A better battery tester capable of faster lifetime prediction would thus reduce the time and cost associated with developing future battery systems.

TECHNICAL OPPORTUNITY

The key opportunity for battery testing technology is the recognition that lifetime prediction can be greatly improved with increased measurement precision. However, better battery testing devices for transportation and stationary energy storage face the challenge of achieving precision measurement under the difficult conditions associated with high-current testing, where transients in temperature and in electrical signals affect the stability of measurements. High precision testing for large, high-power batteries requires new approaches to circuit design, advanced materials for stability in measurement, and expertise in calibration.

INNOVATION DEMONSTRATION



Researchers within Ford Motor Company established a collaboration with Arbin Instruments, Sandia National Lab, and Montana Tech University to develop the application of high-precision testing to meaningful load profiles and larger capacity batteries employed in real world applications. Their project includes the design, build, calibration, and evaluation of a battery tester with the goal of an 8X improvement in voltage measurement precision and 4X improvement in current measurement precision over today's leading testers. The project team's key enabler was its innovative circuit design and thermal management approach to reduce noise and maintain stability. These system design innovations were integrated with 24-bit conversion to achieve the dramatic improvement in precision over state of the art (16-bit) testers.

Forecasting a battery's useful life is accomplished by cycling the battery between states of charge and discharge, and the data collected during this cycling is used to assess the aging of the electrochemical cell. The challenge in effectively forecasting useful life in a timely manner is closely tied to the precision of the tester. With the team's improved testing precision, the estimation of Columbic Efficiency (CE, the ratio of a cell's output upon discharge to the input upon charge, a key parameter for aging studies), the Ford Project Team's tester achieves a CE precision of 50 ppm (±0.005%), as compared to state-of-the-art testers, which can only reach 350 ppm precision (±0.035%).

The increased precision of this battery tester enables prediction of battery lifetime in 4X less testing time (2.5-7.5% of the batteries' intended life rather than 10-30%) compared to a state-of-the-art tester. Beyond lifetime prediction itself, this new level of high-precision data will enable improved analytical capabilities for identification of degradation mechanisms occurring within the electrochemical cell. For example, the unprecedented precision and stability of the tester have allowed the team to detect for the first time sub-100 µAh trends in capacity fade directly related to the state of charge of the cell before, during, and after diagnostic cycles. These trends were too small to detect with standard testers, and offer new and previously unavailable insights to the effects of calendar aging and cycling on cells at different states of charge. The team is also applying these approaches to detect and characterize degradation across different cell chemistries and current profiles.

PATHWAY TO ECONOMIC IMPACT

Team member Arbin Instruments is a leading supplier of testing instrumentation for the battery, super capacitor, and fuel cell markets with headquarters and production facility located in College Station, TX. Arbin Instruments is bringing this system to market in a new series of precision testers, which became available for order in Fall of 2015.

LONG-TERM IMPACTS

At a time of significant innovation and competition among different battery technologies, this improved testing approach for battery research helps to reduce the bottleneck associated with battery lifetime validation. Different applications have very different needs, ranging from high power, highly transient profiles (such as those used for hybrid vehicles or for frequency regulation in grid storage), to more moderate power with less frequent ramping (such as battery electric vehicles or load shifting in grid storage). The ability to more rapidly predict and validate cell lifetime in relevant use conditions will greatly benefit the design of new battery systems, and will aid in the selection and development of the correct cell technology for an intended application.

Additionally, it is expected that the full extent of such an instrument's value will increase as scientific advances continue for energy storage. For example, high-precision data on battery degradation will improve the analytics capability for users by revealing degradation mechanisms that may not be discernible with existing testers. These insights will aid the development of emerging model-predictive control schemes to optimize lifetime and performance of long-life energy storage devices being developed for both the transportation and electricity distribution markets. The full impact of this innovative tool will be measured by the scientists that it empowers to discover new trends and indicators that were previously not obtainable.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the Ford team's project has generated four invention disclosures to ARPA-E and one U.S. Patent and Trademark Office (PTO) patent application. The team has also published the scientific underpinnings of the technology in the open literature:

Masias, A., (2015). *Electrochemical Prozac Relieving Battery Anxiety through Life and Safety Research*. The BRIDGE NATIONAL ACADEMY OF ENGINEERING, Spring 2015, p. 13-20.

CHANGING WHAT'S POSSIBLE

ADVANCED SENSORS FOR EFFECTIVE BATTERY MANAGEMENT SYSTEMS

Updated: February 24, 2016

PROJECT TITLE: Smart Embedded Network of Sensors with Optical Readout (SENSOR)	
PROGRAM: Advanced Management and Protection of Energy Storage Devices (AMPED)	
AWARD: $4,017,132	
PROJECT TEAM: Palo Alto Research Center (PARC) (Lead); LG Chem Power, Inc.	
PROJECT TERM: October 2012 – September 2015	
PRINCIPAL INVESTIGATOR (PI): Dr. Ajay Raghavan	

TECHNICAL CHALLENGE

Achieving widespread adoption of hybrid electric and electric vehicles (xEVs) requires substantial improvement in battery performance while also reducing the cost of the battery system. Although it is essential to minimize the volume and weight of the battery systems, the batteries used in today's xEVs are one and a quarter to two times larger than actually needed to power a vehicle. The reason for this oversizing is that today's battery management systems (BMS) have limited information on the state (state-of-charge, state-of-health, and state-of-power; generally referred to as "SOX") of the many individual cells that make up the battery. As a consequence, a safety margin of unused capacity must be built in. To obtain more value from both present and future batteries, innovations in BMS are needed to monitor the batteries, and optimize overall battery performance, longevity, and safety and thus allow more complete use of the available capacity.

TECHNICAL OPPORTUNITY

Traditional BMS use a small number of sensors connected by electrical wires across the battery pack. Due to the fact that sensor placement and wiring adds weight, cost, and complexity, battery packs typically utilize a small number of sensors, preventing individual measurements of the cells. Advances in sensor technology, and the transmission and analysis of signals now make it possible to revisit the traditional design of BMS and develop more complete, cell-level sensing in simpler, lower cost systems.

INNOVATION DEMONSTRATION

The PARC team proposed a transformational approach to battery management based on fiber-optic (FO) sensors. PARC's newly developed low-cost, high-accuracy FO wavelength shift detector was a key enabling technology for the project. The technical benefits of this approach include the intrinsic electrical isolation of a FO system, the variety of sensing modalities possible (strain, temperature, etc.), the capability to multiplex multiple sensors along the same FO cable, and the potential to collect data from all the cells rapidly. Preliminary assessments indicate the potential to reduce system cost by 10-15 percent and trim pack oversizing.

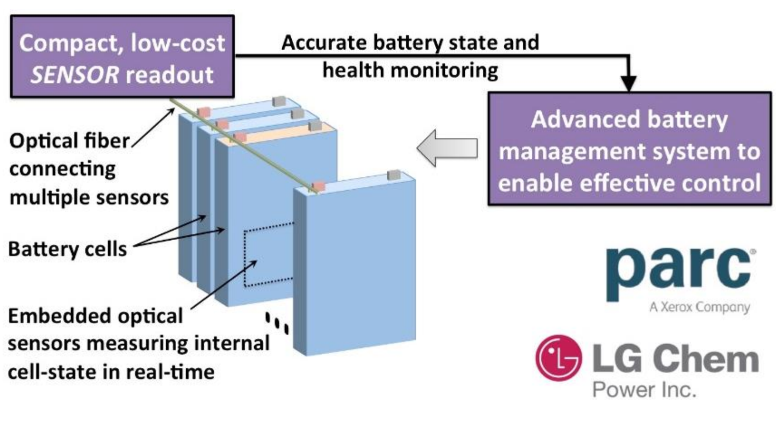


Figure 1. Schematic diagram of PARC's fiber optic sensor network

The PARC team has developed embedded FO sensors, demonstrated their embedding into the electrode stacks of large-format xEV-grade cells, and completed initial demonstration of SOX estimates in initial module-level tests across various xEV use cases. The project team has also prototyped and tested the optical monitoring system that enables comprehensive battery pack performance management. Their prototype BMS, applied to a battery system with more than 25% oversize, reduced pack weight by five percent and cost by 10%.

PARC's system combines embedded FO sensors and smart algorithms to monitor internal cell parameters, estimate state information, and predict remaining battery energy. The developed read-out technology can monitor hundreds of multiplexed FO sensors with high resolution (50 fm or better). The sensor network utilizes FO sensors attached to and embedded within the battery cell itself and advanced algorithms enabling 2.5% or better accuracy in SOX estimation.

PATHWAY TO ECONOMIC IMPACT

Cost analysis of a representative xEV battery system shows that PARC's optical sensor technology can allow downsizing of the battery pack to save hundreds of dollars in the cost of battery cells while at the same time bringing down the cost of the BMS itself. There are also significant safety and performance benefits for a BMS employing an all-optical sensor and communication technology that does not require electrical isolation and is not subject to electrical noise.

In October 2015, PARC along with their partner LG Chem Power, Inc. and a new auto original equipment manufacturer partner initiated testing and evaluation of the SENSOR system's application to a plug-in hybrid electric vehicle module. This module will contain more than 24 large-format Li-ion cells, and will undergo a number of pack-level load cycling simulations as well as shock and vibration experiments to prove out system worthiness for this auto industry partner's future xEV models.

LONG-TERM IMPACTS

PARC's technology, while developed for initial use in xEVs, will also be applicable to batteries for grid storage and other advanced energy storage applications. The use of optical fibers, which remove the need for electrical connectors for sensors and communications in the BMS, will provide a special safety benefit in high voltage and other critical high-energy density systems.

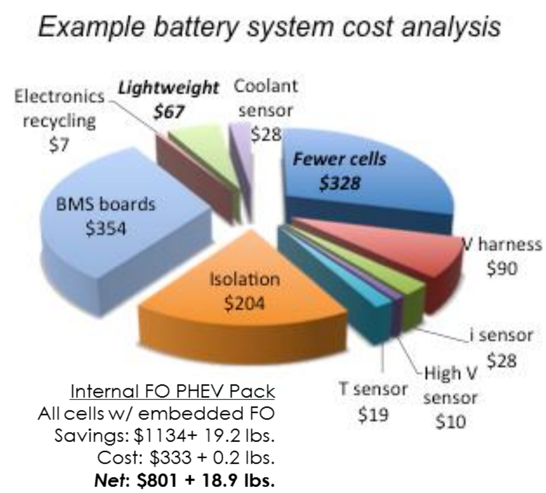


Figure 2. Example battery system cost analysis

While the initial application is for existing Li-ion batteries, the improved controls are likely to be even more valuable in future batteries with new chemistries that support higher specific energies. These new batteries are likely to require improved BMS to maintain performance and safety. PARC is working on applications of its SENSOR system for such developmental battery research.

The dominant cost driver for EVs is the energy storage system, and a United States Advanced Battery Consortium analysis sets targets of $125/kWh cost and a specific energy of 250 Wh/kg to make EVs economically competitive.[3] Despite rapid progress, EV-grade Li-ion batteries still cost about $400/kWh with specific energy less than 150 Wh/kg according to worldwide industry estimation in 2014, with industry leaders driving costs down toward $300/kWh. The PARC BMS has demonstrated potential to support both cost reductions, and increases in specific energy beyond those that will be delivered with continuing improvements in battery chemistry. By enabling significant improvements in battery size, performance, and safety in electric vehicles, PARC's technology could potentially promote greater adoption of hybrid and electric vehicles, as well as support the growth of grid-level energy storage based on batteries.

[3] Neubauer, J., Pesaran, A., Bae, C., Elder, R., & Cunningham, B. (2014). Updating United States Advanced Battery Consortium and Department of Energy battery technology targets for battery electric vehicles. Journal of Power Sources, 271, 614-621.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the PARC team's project has generated 14 invention disclosures to ARPA-E, eight U.S. Patent and Trademark Office (PTO) patent applications and two patents:

Patents

"Monitoring/managing electrochemical energy device using detected intercalation stage changes," (12/8/2015), Patent No 9209494, Washington, DC: U.S. Patent and Trademark Office.

"Sensor apparatus and method based on wavelength centroid detection," (12/1/2015), Patent No 9201000, Washington, DC: U.S. Patent and Trademark Office.

The PARC team has also published the scientific underpinnings of the SENSOR technology extensively in the open literature. A partial list of publications is provided below. Further information on the project is available at www.parc.com/sensor.

Publications

"Embedded fiber optic sensors for in situ and in-operando monitoring of advanced batteries," J. Schwartz, K. Arakaki, P. Kiesel, A. Raghavan, W. Sommer, A. Lochbaum, A. Ganguli, A. Hegyi, B. Saha, C.-J. Bae, H. Hah, C. Kim, and M. Alamgir, MRS Proceedings, 1740, mrsf14-1740-z01-08, 2015.

"Fast and Slow Ion Diffusion Processes in Lithium Ion Pouch Cells during Cycling Observed with Fiber Optic Strain Sensors," Sommer, L.; Kiesel, P.; Ganguli, A..; Lochbaum, A.; Saha, B.; Schwartz, J.; Bae, C.; Alamgir, M.; Raghavan, A., *Journal of Power Sources,* v. 296, p. 46-52, 2015.

"High-resolution wavelength shift detection of optical signals with low-cost, compact readouts," A. Schuh, A. Hegyi, A. Raghavan, A. Lochbaum, J. Schwartz, B. Saha, A. Ganguli, and P. Kiesel, Proc. SPIE 9480, Fiber Optic Sensors and Applications XII, 94800B (3 June 2015); doi: 10.1117/12.2177478.

"Monitoring of Intercalation Stages in Lithium-Ion Cells Over Charge-Discharge Cycles with Fiber Optic Sensors," Sommer, L.; Raghavan, A.; Kiesel, P.; Saha, B.; Schwartz, J.; Lochbaum, A.; Ganguli, A.; Bae, C.; Alamgir, M., *Journal of the Electrochemical Society*, v. 162(14), A2664-2669, 2015.

CHANGING WHAT'S POSSIBLE

CREATING DOUBLE ENERGY DENSITY ANODES FOR LITHIUM-ION BATTERIES

Updated: February 15, 2016

PROJECT TITLE: Doubling the Charge Density of Anodes in Lithium-Ion Batteries for Transportation	
PROGRAM: Small Business Innovation Research (SBIR)	
AWARD: $2,975,000 + $250,000	
PROJECT TEAM: Sila Nanotechnologies (Lead); Georgia Institute of Technology	
PROJECT TERM: October 2012 – March 2016	
PRINCIPAL INVESTIGATOR (PI): Gene Berdichevsky	

TECHNICAL CHALLENGE

To realize the benefits of wide-spread electric vehicle adoption, battery size and cost both need to be reduced to provide a driving range of at least 300 miles at a price competitive with conventional vehicles. Changing the composition of batteries to include different chemicals that can provide higher energy density (the amount of energy relative to the size of the battery), is a technology focus for addressing this challenge. However, each new chemistry brings new challenges to the battery design. One promising approach, that could increase the energy density of lithium (Li)-ion batteries as much as 40%, is to use silicon as the active material in the negative electrode (anode). Unfortunately, the reactions of lithium and silicon cause severe swelling and contraction of the silicon anode material as the battery charges and discharges, and this has defeated previous attempts to create such a battery. These challenges have hindered the introduction of silicon in Li-ion batteries, and if they could be overcome, it would provide a real opportunity for increasing the capacity of Li-ion batteries.

TECHNICAL OPPORTUNITY

By controlling particle structures at the nano-scale through recent advances in materials synthesis, scientists are now able to provide unique opportunities to address the silicon anode challenge. In particular, a broad range of synthesis techniques have been emerging that allow tailoring particle size, pore size, chemistry, and surface properties of silicon-based composites. These synthesis techniques provide a potential platform to engineer Si-based structures with the ability to manage the volume changes during reaction with lithium, while also minimizing deleterious surface reactions

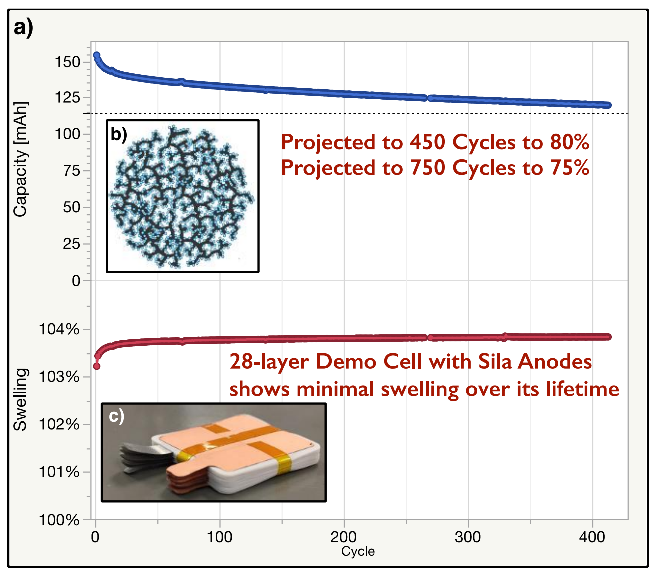


Figure 1. (a) Sila anodes demonstrate excellent cycle life in matched full cells and <1%, cell level swelling over 400+ cycles (b) Sila's technology is based on work published by in 2010 in Nature Materials (c) Sila's stacked demo cell platform uses all commercial components and build methods paired with Sila's proprietary anodes

INNOVATION DEMONSTRATION

The Sila team has used a unique approach to exploiting nanostructured materials to enable stable cells with silicon anodes. In 2010, members of the Georgia Institute of Technology project team published their work in *Nature Materials* (Magasinki et al.) showing that a nanostructured silicon-based particle could be synthesized, coated with carbon, bound with the traditional anode binder polyvinylidene fluoride (PVDF) and used in a half cell to reversibly cycle lithium ions.

In 2011, Sila Nanotechnologies Inc. was founded by a team of Silicon Valley entrepreneurs in collaboration with the Georgia Institute of Technology to continue this research and development (R&D). Further evolution of this material concept resulted in building novel composite anode powders, where a silicon-comprising porous core was encased in an ionically conductive shell. In this particle architecture, silicon can accept lithium without inducing significant particle expansion during charging. In addition, these micron-sized composite particles exhibit small outer surface areas in contact with electrolytes, which minimizes undesirable side reactions. The outer shells allow for rapid conduction of lithium ions, while also preventing uncontrolled reactions between silicon and the liquid electrolyte. In this manner, a vast portion of silicon's specific capacity can be realized without inducing rapid cell degradation. Sila's advanced synthesis methods allow the engineering of such nanocomposites, and then production of these micron-size composite powders at the kilogram scale with a path to production at the ton scale.

During the ARPA-E-funded development project, Sila reproducibly manufactured thousands of ~10 mAh single layer pouch cells and now has initial 100-200mAh multi-layer demo cells capable of retaining 80% current capacity after as many as 400-600 cycles at C/3-C/2 rates. The company's original R&D scale reactors allowed for up to 100g (~150Ah) of anode material production per day. Sila has completed the design and nearly completed construction of a pilot scale reactor to produce their proprietary silicon-based anode material at a scale of kilograms per day. Additionally, Sila has since completed construction of a robot assembly unit to make stacked pouch cells.

PATHWAY TO ECONOMIC IMPACT

Sila's ongoing silicon anode project seeks to make the first batteries with stable silicon anodes that can cycle for hundreds of times while staying within industry durability, performance, and cost specifications.

Sila's first commercial deployments in portable consumer electronics is targeted to start in 2017, followed by larger format pouch cells for automotive applications in 2020-2022. Specifically, these forecasted dates are aided by sizeable private investment from financial investors, including top-tier venture firms Matrix Partners and Sutter Hill Ventures, as well as industrial partners in both the consumer electronics and automotive spaces.

LONG-TERM IMPACTS

Today's commercially available Li-ion batteries for electric vehicles cost about $200/kWh at the cell-level, with pack costs of $300/kWh. At these levels, a battery pack that can deliver sufficient energy for a 300-mile range (85 kWh) would cost roughly $25,000. Widespread adoption of electric vehicles will require battery cells with more than double current state-of-the-art energy densities (1,000 Wh/L) at a third of the cost (less than $100/kWh). Plans for manufacturing scale-up of Li-ion batteries to 35 GWh/year may bring costs down to less than $200/kWh.

When a silicon-based anode replaces the graphite in today's Li-ion batteries, a cell energy density of 1200 Wh/L becomes possible when coupled with advanced cathode materials. Sila's anodes have the potential to reduce the cell cost to less than $100/kWh, a target that would support electric vehicle goals. Such a battery would also be cost competitive for grid applications, including renewable energy storage. The planned commercial deployment and testing of the new technology will be an important step in developing the experience base needed to incentivize uptake in electric vehicles and grid applications.

More general, the strategy of encapsulated nanostructures can be broadly applicable to other battery chemistries and possibly other industries as well: the nanostructuring addresses mechanical failure while encapsulation minimizes surface side reactions.

HIGH ENERGY DENSITY ULTRACAPACITORS

Updated: July 18, 2016

PROJECT TITLE: Low-Cost, High Energy and Power Density, Nanotube-Enhanced Ultracapacitors	
PROGRAM: OPEN 2009	
AWARD: $5,349,932	
PROJECT TEAM: FastCap Systems (Lead), Massachusetts Institute of Technology	
PROJECT TERM: April 2010 – December 2013	
PRINCIPAL INVESTIGATOR (PI): Dr. Ricardo Signorelli	

TECHNICAL CHALLENGE

Storage-related challenges are important to the widespread adoption of hybrid electric vehicles (HEVs) and electric vehicles (EVs). EVs are propelled by an electric motor that, in turn, is powered by a rechargeable battery. The state of the art lithium (Li)-ion battery can store considerable power but it charges and recharges slowly, limiting the range that an EV can travel. Supercapacitors, on the other hand, can charge and discharge rapidly but store 10 times less energy than a li-ion battery. Increasing the charge storage in supercapacitors ("supercaps") at competitive cost, while retaining the charge-discharge rate would be disruptive, enabling their use in a variety of storage applications including EV's.

TECHNICAL OPPORTUNITY

The energy storage mechanism of supercaps is solely electrostatic. Since charge storage does not involve chemical reactions, as it does in batteries, supercaps can have millions of rapid charge-discharge cycles without capacitance degradation and with unlimited shelf-life. The drawback of today's supercaps, however, is their low energy storage per unit volume and weight (~5% of the Li-ion battery) and their high upfront cost (~10X more than those of Li-ion batteries). Technical opportunities for increasing the supercapacitor power density result from increasing scientific understanding of how to control surface structure at a nanometer scale, as well as advances in the ability to monitor and control chemical composition.

INNOVATION DEMONSTRATION

An ultracapacitor is an electronic device where energy is stored electrostatically. The energy density that the device can store is proportional to the electrode surface area. FastCap proposed increasing the energy density of the device by introducing an electrode comprising carbon nanotubes ("CNT"). The narrowly spaced nanotubes would provide considerable surface area, which, in turn, would translate into higher energy density. FastCap designed a composite electrode comprising purified amorphous carbon and 5-10% carbon nanotubes. The performance of the supercap with a carbon nanotube composite electrode shows a 3X improvement relative to the bare carbon electrode without CNT's.

Figure 1. Carbon nanotube fabrication line at FastCap

PATHWAY TO ECONOMIC IMPACT

Based on the development of its initial technical results under ARPA-E support, FastCap has developed its Extreme Environment line of supercaps, designed to enable the use of safer, lower power batteries while providing the requisite energy and power to drive actuators with the added benefits of extending battery runtime and reducing operating costs.

FastCap's supercaps have been successfully commercialized for down hole drilling operations in the oil and gas industry. FastCap has also developed supercaps for space and geothermal application, the former funded by NASA. FastCap Systems technology's value proposition currently provides high energy density and power density available with long life performance and a wide window of operating temperatures.

LONG-TERM IMPACTS

FastCap has developed ultracapacitors with record supercap performance at E=18 Wh/L and P=120kW/L. Significant increases in performance may be possible if the operational voltage can be further increased.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of May 2016, the FastCap Systems project has submitted 17 subject invention disclosures to ARPA-E, filed 7 non-provisional U.S. Patent and Trademark Office (PTO) patent applications, and received 3 patents issued by the U.S. PTO.

"Energy storage media for ultracapacitors". (2015) *US Patent No. 9,218,917*. Washington, DC: U.S. Patent and Trademark Office.

"High power and high energy electrodes using carbon nanotubes". (2015) *US Patent No. 9,001,495*. Washington, DC: U.S. Patent and Trademark Office.

"In-line manufacture of carbon nanotubes". (2015) *US Patent No. 9,017,634*. Washington, DC: U.S. Patent and Trademark Office.

CONFORMABLE NATURAL GAS TANKS

Updated: February 24, 2016

PROJECT TITLE: Fully and Intricately Conformable, Single-Piece, Mass-Manufacturable High-Pressure Gas Storage Tanks
PROGRAM: Methane Opportunities for Vehicular Energy (MOVE)
AWARD: $5,000,000
PROJECT TEAM: REL, Inc. (Lead)
PROJECT TERM: September 2012 – March 2016
PRINCIPAL INVESTIGATOR (PI): Dr. Adam Loukus

TECHNICAL CHALLENGE

Natural gas vehicles (NGV) provide a significant opportunity to increase U.S. energy security, enabled by the substantial increases in U.S. natural gas reserves and annual production over the past ten years. However, the large, cumbersome, and expensive on-board fuel tanks presently used in NGVs create a major barrier to increased utilization of natural gas as a transportation fuel. Additionally, the low volumetric density of compressed natural gas—26.9% of the volumetric energy density of gasoline—limits the driving range of NGVs and makes cost-effective storage solutions an even more important challenge. Significant improvements must be made to the capacity, conformability, and cost of on-board storage to accelerate NGV adoption.

TECHNICAL OPPORTUNITY

Currently NGVs are outfitted with bulky and expensive cylindrical pressure vessels that can be difficult to fit within the car without compromising passenger utility. The technical potential of a conformable gas tank based on innovative geometries, lighter materials and a new overall design is the opportunity needed to overcome key market barriers that NGVs currently face. Such a tank could potentially be conformed to a variety of shapes with higher storage capacity than current cylindrical tanks.

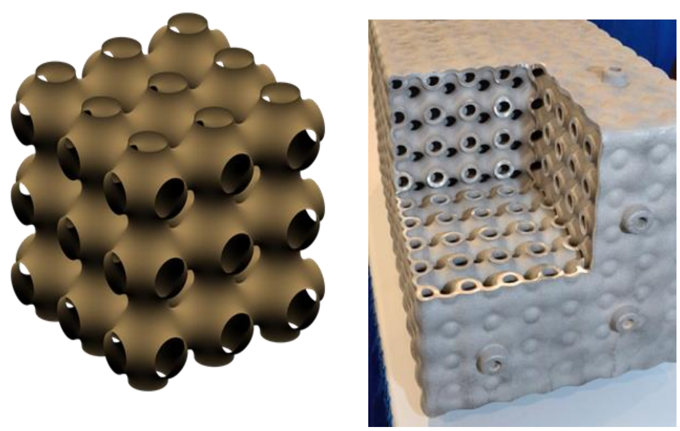


Figure 1. The Schwarz P-surface structure of the REL conformable tank, shown schematically and in cross section on a demonstration tank

INNOVATION DEMONSTRATION

Traditional natural gas storage tanks are cylindrical with hemisphere caps, which take up significant amounts of space within a vehicle. REL developed new casting methods to create an internally structured gas tank that enables the manufacture of a tank of arbitrary shape. The team's natural gas tank design contains an internal structure to add strength and durability to the walls. It resembles the skeletal structure of a sea urchin. The shape is a Schwarz P-surface, which allows for internal stresses to be distributed throughout the internal tank structure. REL used its proprietary casting technologies to develop a high integrity casting to fabricate the complex inner geometry.

The casting innovations include a sacrificial core structure, thermal isolation die coating, and distinct yet complementary field-assisted casting techniques. The tank technology utilizes an efficient internal tank structure, has separate internal volumes, and has a substantial conformability advantage over current cylindrical high pressure tanks. REL has developed small-scale prototypes and intends to scale up to a full-sized prototype tank operating within a vehicle.

PATHWAY TO ECONOMIC IMPACT

Any storage tank technology will need to be certified to confirm safe performance in automotive conditions before it can enter the market. To address this regulatory barrier to market entry for novel tank technologies, appropriate standards for conformable tanks will need to be developed and validated. To that end, REL has become a member of the Canadian Standards Association (CSA) Natural Gas Vehicle (NGV) 2/HGV 2 Technical Advisory Group (TAG) for compressed natural gas and compressed hydrogen vehicle fuel containers. They have joined this group to address technical issues and draft proposed standards text for industry review and comment and finally for approval as an American National Standard. The goal is to develop and approve a new edition of NGV2 that paves a path for certification of conformable fuel storage tank technologies.

REL's initial target application is natural gas pickup trucks, which typically carry the cylindrical natural gas tank in the truck bed. Replacing the cylinder in the bed of the truck will allow owners to use a larger percentage of their cargo space. REL believes it can design a 20 gasoline gallon equivalent (GGE) tank to fit on a Chevy Silverado chassis without compromising any cargo space.

In December, 2014, REL and Michigan Technological University jointly announced $2.1 million in funding (structured as a three-year investment) from Southwestern Energy (SWN).[4] The project is targeting mid-2016 for full scale tanks integrated into a Chevy 1500 demonstration truck. REL will design and build, test, and mount, and finally equip vehicles of SWN's fleet with the developed tank technology. Prototype quarter-scale tanks have already been burst pressure tested and have achieved the critical 8100 psi milestone. The successful quarter-scale tank will hold approximately 12 GGE for further integration and testing purposes. In-house NGV2 testing continues and third party testing and validation will commence in the first quarter of 2016.

LONG-TERM IMPACTS

About 27% of oil consumed in the U.S. is imported, and about 71% of U.S. oil consumption goes to transportation. The U.S. Energy Information Administration (EIA) projects that natural gas use in vehicles will reach almost 1 trillion cubic feet by 2040, compared with the 40 billion cubic feet consumed by natural gas vehicles in 2011. This increase would displace about 700,000 barrels per day of other motor fuels. Consumer willingness to adopt NGVs, particularly for light-duty applications, will be increased by technology innovations such as REL's conformable gas tank, which frees up vehicle cargo space and allows vehicles to carry more natural gas, improving range between refueling. This improved performance thus enables further reduction of U.S. dependence on imported oil for transportation needs as well as overall greenhouse gas emissions.

INTELLECTUAL PROPERTY

As of February 2016, the REL team's project has generated five invention disclosures to ARPA-E, five U.S. non-provisional patent applications, and one patent issued by the U.S. PTO:

"Thermal Isolation for Casting Articles". *US Patent 9180511*. (2015) Washington, DC: U.S. Patent and Trademark Office.

[4] http://www.mtu.edu/news/stories/2014/december/michigan-tech-calumet-firm-receive-21-million-southwestern-energy-company.html

CHANGING WHAT'S POSSIBLE

DEVELOPING ACCESSIBLE NATURAL GAS COMPRESSION

Updated: February 24, 2016

PROJECT TITLE: Vehicle-Integrated Natural Gas Compressor	
PROGRAM: Methane Opportunities for Vehicular Energy (MOVE)	
AWARD: $3,600,000	
PROJECT TEAM: Onboard Dynamics (Lead); Oregon State University	
PROJECT TERM: October 2012 – August 2016	
PRINCIPAL INVESTIGATOR (PI): Ms. Rita Hansen	

TECHNICAL CHALLENGE

Natural gas vehicles (NGV) provide a significant opportunity to reduce emissions and increase U.S. energy security, enabled by the substantial increases in U.S. natural gas reserves and annual production over the past ten years. However, there are fewer than 900 public compressed natural gas refueling stations in the U.S. today (vs. over 150,000 gasoline stations), which represents a significant obstacle to the increased adoption of NGVs. Furthermore, the current cost of a natural gas refueling station is about $1.6 million, compared to about $100,000 for gasoline. At these costs, a natural gas infrastructure that supports light, medium, and heavy-duty fleet vehicles presents an economic barrier. Significant improvements must be made to the infrastructure and accessibility of compressed natural gas to accelerate NGV adoption.

TECHNICAL OPPORTUNITY

There are over 70 million homes and commercial sites with access to natural gas delivered at low or medium pressure. Low-cost, easily deployed gas compression systems that can work from this distribution network would provide a natural infrastructure for supporting natural gas vehicles. However, conventional compression systems capable of tapping into a low-pressure site now cost over $5,000 and take over 12 hours to fill a vehicle with a 10-gallon tank. In addition, these systems require access to electric power. Using internal combustion engines with integrated natural gas compression capability provides an opportunity for many applications to minimize compression systems costs and complexity.

INNOVATION DEMONSTRATION

Onboard Dynamics' (ObDI) received an ARPA-E award for development of a mechanism in which a natural-gas driven internal combustion engine (ICE) can be used to compress low pressure natural gas to 250 bar (3,600 psi) for storage. The engine compressor takes advantage of the existing compression capability of an internal combustion engine. Two of the three compression stages occur in the engine, which can be the engine in a natural-gas powered vehicle itself.

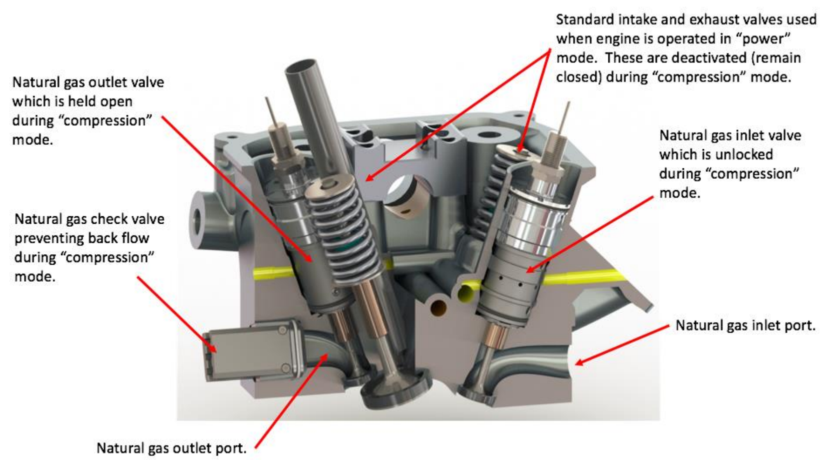


Figure 1: ObDI's modified cylinder head, which allows both compression and normal operation.

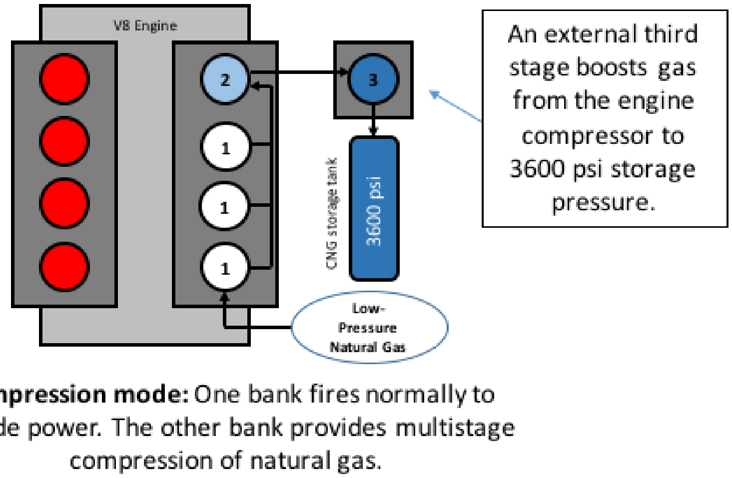


Figure 2: V8 engine compressor in compressor mode. One bank fires normally to provide power. The other bank provides multistage compression of natural gas. An external third stage boosts gas from the engine compressor to 3600 psi storage pressure.

The project team developed a custom cylinder head (Figure 1) in which the engine cylinders can be used for both multistage compression and normal combustion. The custom engine head contains the manifolding for the staged compression, and it enables valve deactivation, which is necessary for the cylinders to function both as compressors and combustion chambers. Ultimately, the engine would then have the ability both to power a vehicle and to compress natural gas.

Natural gas compression takes place in one cylinder bank of the engine, with the other cylinder bank providing power (Figure 2). When the tank is filled, the vehicle can revert back to transportation mode and the stored compressed natural gas (CNG) will be consumed by the ICE to drive the vehicle. The Onboard Dynamics' engine compressor thus allows a vehicle to refuel itself, and other vehicles, at any natural gas source.

Subject to further development, if this onboard compression capability is incorporated as part of the vehicle manufactured directly to run on natural gas, the incremental costs could be less than $1,000/vehicle.

PATHWAY TO ECONOMIC IMPACT

ObDI was launched as a startup company to further develop and commercialize the CNG technology that originated at Oregon State University (OSU). As part of its ARPA-E project, ObDI designed, fabricated, and installed a prototype custom cylinder head onto a Ford 6.2 liter V8 engine and demonstrated its ability to successfully compress air on a dynamometer test stand.

ObDI expects the first markets for the compressor technology to draw on the technology's characteristics of being self-powered (e.g. using natural gas directly and not requiring an electrical connection) and being economical at small scale. Based on market research conducted by ARPA-E, there is a market for mobile electrical compressors such as the ObDI system. The project team hopes to provide an economically competitive product and ObDI is evaluating this as a first market and a path to driving down production costs, while continuing parallel development of the in-vehicle option.

LONG-TERM IMPACTS

Reduced natural gas compression costs are a key to increased use of natural gas as a low-emission alternative or transitional transportation fuel. This is particularly important as a complement to electrification and the use of biofuels. ObDI's innovation could help remove the barrier of developing a natural gas refueling infrastructure. Converting a significant fraction of U.S. vehicles to natural gas could lead to the same fractional decrease in present U.S. levels of imported oil.

INTELLECTUAL PROPERTY

As of February 2016, the ObDI project has resulted in five subject invention disclosures to ARPA-E and two U.S. PTO patent applications.

DEVELOPMENT OF HIGH-OUTPUT, LOW-INPUT ENERGY BEETS

Updated: June 9, 2016

PROJECT TITLE: Development of High-Output, Low-Input Energy Beets	
PROGRAM: OPEN 2012	
AWARD: $2,050,471	
PROJECT TEAM: Plant Sensory Systems, LLC (Lead), North Dakota State University	
PROJECT TERM: March 2013 – March 2017	
PRINCIPAL INVESTIGATOR (PI): Dr. Frank Turano	

TECHNICAL CHALLENGE

Biofuels offer renewable alternatives to petroleum-based fuels that can reduce net greenhouse gas (GHG) emissions dramatically. Even with the expected improvements in electric vehicle technologies, liquid fuels are likely to remain in significant niches within the transportation sector. Today's vision for cost-competitive domestically produced biofuels are hampered by three key issues: 1) Crops intended for biofuel production require large tracts of arable land that may compete with food crops; 2) Biomass is not easily digested and requires an expensive or inefficient process to break down into its components; and 3) Oil-rich crops do not provide enough energy yield per unit area to be a cost-effective alternative for production of transportation fuel at scale.

TECHNICAL OPPORTUNITY

Advances in plant biology have shown that the non-protein amino acid, gamma-aminobutyric acid (GABA) rapidly accumulates in plant tissues in response to biotic and abiotic stress, and regulates plant growth. GABA has been observed to increase the sugar content in grapes when applied exogenously, and in canola engineered to have increased GABA levels. The potential to increase sugar content would be particularly attractive for sugarbeets, which produce high levels of fermentable sugars per acre and are easier to convert into biofuel than starch from corn grain. GABA appears to play a role in nitrogen metabolism, subsequently if GABA regulation can also be used to reduce fertilizer usage in the field, this would lead to less N_2O greenhouse gas emissions and nitrogen run-off. A feedstock that produces similar levels of fermentable sugar as corn, but with reduced agronomic inputs, would qualify under the Renewable Fuels Standard as an advanced biofuel and enjoy market benefits over corn grain ethanol.

INNOVATION DEMONSTRATION

Plant Sensory Systems' (PSS) project goals were to increase sugar yield from beets by 30% over standard beet sugar yields today (4.98 tons/acre) and reduce the amount of nitrogen fertilizer needed. The PSS team's approach was to use their proprietary promoters and genes that, when expressed in plants, increases GABA production and yields a Nitrogen Use Efficiency and Stress Tolerance (NUEST) trait.

Figure 1. PSS' hybrid beet seed production.

PSS introduced its proprietary NUEST genes into sugarbeets and evaluated the trait phenotype in the greenhouse under controlled conditions. The best performing NUEST plants had both significantly increased brix (free extractable sugars) and root biomass compared to control beets. On average, the best NUEST lines yielded approximately 40% more sugar per plant under laboratory conditions. Experiments to quantify the effect of the NUEST trait on nitrogen-based fertilizer use efficiency were initiated in early 2016.

In addition, PSS made a NUEST gene construct that does not contain any DNA elements that would be regulated as transgenic by the United States Department of Agriculture, and transformed this "commercial" construct into beets. If successful, this approach would avoid the lengthy and costly regulatory approval process required for the transgenic beats.

PSS developed a method for inducing flowering in sugarbeets that reduced the time to generate seed by one year versus conventional growing processes. This method allowed the plants to generate sufficient seed to plant small field plots in Colorado in 2016 and bulk up enough seed to plant several field trials in the fall of 2016.

To determine the best first market opportunity, PSS worked with North Dakota State University (NDSU) on a techno-economic analysis (TEA) for different regions of the U.S. The best rate of return to growers was projected for the Southeast due to low land costs and favorable environmental conditions. With this insight, PSS focused its efforts toward developing non-transgenic beet hybrids optimized for growth in the Southeast. Small-scale field trials of hybrids developed with traits optimized for growth in Southeast were started in early 2016 in Florida to assess field performance, and to introduce Florida citrus growers to a new crop rotation. Once validated in the field, the commercial NUEST trait will be incorporated into these hybrids to increase the sugar yield of the crop.

PATHWAY TO ECONOMIC IMPACT

Supported by data from early field trials and economic models, PSS has identified grower-investors who will install supporting beet ethanol fermentation facilities starting in 2017. PSS has spun off a startup company "Just-Beets" with a commercialization plan offering a sustainable value capture and commercial ramp up of the early-stage bioenergy R&D supported by ARPA-E.

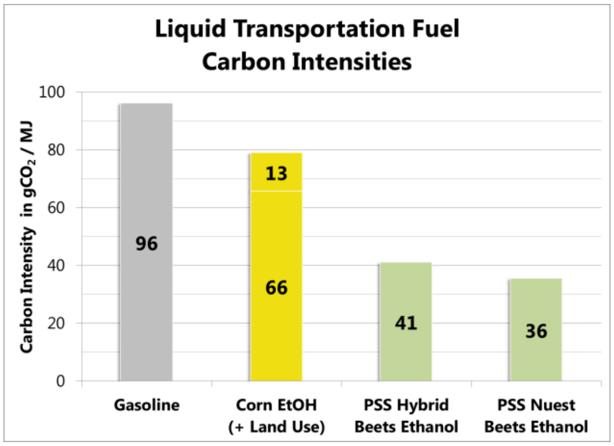


Figure 2. The carbon intensities of ethanol production from PSS beets versus corn and conventional petroleum gasoline.

Based on the experimentally validated NDSU model, the expected beet yield in Florida is 38 tons of beets producing 783 gallons of ethanol per acre, 60% greater than existing ethanol yields from corn grain. The co-produced beet pulp fulfills a shortage of cattle feed caused by the declining availability of citrus pulp and also adds additional economic value. Building on the local agricultural community's support, this PSS beet technology could provide up to $568 million in replacement economic value in Florida for the 500,000 acres currently fallowed by Citrus Greening, a disease of citrus caused by a vector-transmitted pathogen.

Florida's citrus industry generates $10 billion dollars annually and employs 76,000 residents. However, Citrus Greening disease has tripled expenses for growers and led to the smallest crop in more than 50 years.[5] PSS has identified a market entry opportunity, and early field data demonstrates promise for a viable economic replacement crop capable of stabilizing agricultural employment. Economic analysis work done by PSS and NDSU predicts that ethanol production from PSS hybrid beet technology will create $0.88/gal profit for producers, and the follow-on NUEST beet technology is expected to produce $1.16/gal in profit.

LONG-TERM IMPACTS

The focus on building a stakeholder network in a primary market (e.g. Florida), with a compelling value proposition, is a model for the successful introduction of new bioenergy crops into complex feedstock supply chains. Subsequently, the PSS team is creating additional economic activity in several more U.S. states with field trials in Alaska, Arkansas, Maryland, and California.

[5] Greg Allen, "How Long Can Florida's Citrus Industry Survive?," *NPR.org*, November 27, 2015, http://www.npr.org/sections/thesalt/2015/11/27/457424528/how-long-can-floridas-citrus-industry-survive.

The second important impact from the ARPA-e funded technology is an opportunity to expand a biofuel industry that: does not compete with staple food products; produces up to 60% more ethanol per acre than corn grain; and significantly lowers the carbon intensity of biofuel. For example, the calculated carbon intensities (CI) of the new PSS beet crops are 41.2 gCO_2/MJ for the hybrid beets and 35.6 gCO_2/MJ for NUEST. The hybrid beet CI in the Southeast is 57% lower than the 96.2 gCO_2/MJ of conventional petroleum fuels and 48% lower than corn grain (Figure 2), qualifying the technology for advanced biofuel certification (application under EPA review).

PRODUCING TERPENE BIOFUELS IN PINE TREES

Updated: June 6, 2016

PROJECT TITLE: Commercial Production of Terpene Biofuels in Pine	
PROGRAM: Plants Engineered to Replace Oil (PETRO)	
AWARD: $6,917,276	
PROJECT TEAM: University of Florida (Lead); Arborgen, University of California-Berkeley, National Renewable Energy Laboratory	
PROJECT TERM: January 2012 – June 2017	
PRINCIPAL INVESTIGATOR (PI): Dr. Gary Peter	

TECHNICAL CHALLENGE

Biofuels offer renewable alternatives to petroleum-based fuels, which can reduce net greenhouse gas (GHG) emissions dramatically. Even with the expected improvements in electric vehicle technologies, liquid fuels are likely to remain the dominant form of energy used in significant niches within the transportation sector, such as long-haul trucking and air transportation. Today's vision for cost-competitive domestically produced biofuels are hampered by three key issues: 1) Crops intended for biofuel production may require large tracts of arable land that at scale can compete with the production of food crops; 2) Most biomass is not easily digested and presently requires an expensive or inefficient process to break down dried biomass (i.e. lignocellulose) into its components; and 3) Today's oil-rich crops do not provide enough of a step up (based on energy yield per unit area) to be a cost-effective alternative for production of transportation fuel at scale.

TECHNICAL OPPORTUNITY

Many plants produce complex chemicals that could be readily transformed into high quality biofuels. For instance, pines have specialized cells that make up resin canals and allow the trees to naturally accumulate moderate levels of terpenes (3-5%) in wood. The terpenes are recovered from harvested trees or from living trees by tapping to extract these fuel precursors throughout the life of the mature tree. However, the natural yield of such chemicals in the plants is too low to allow cost-competitive production of fuels. With improved understanding of developmental and biochemical processes, it is now possible to engineer specific pathways that plants use to create chemicals. This knowledge can be coupled with recent advances of *in vitro* DNA synthesis, which allow scientists to create a large number of possible gene constructs, and test them rapidly to identify those that increase the plant's yield of the desired chemical.

INNOVATION DEMONSTRATION

With ARPA-E support, the University of Florida (UF) has experimented with enhancing fuel production in a species of pine (loblolly) that is currently used in the paper pulping industry.

As shown in Figure 1, the team is pursuing a three-part technical approach: 1) Activation: increasing resin synthesis and storage capacity in wood by modulating developmental regulators of resin canals; 2) Pathway: improving flux through the terpene biosynthetic pathway by alleviating bottlenecks in the metabolic pathway; and 3) Enzyme: developing more active terpene biosynthesis enzymes and channeling of substrates more efficiently through protein engineering to specific terpene molecules with desired fuel properties. These three approaches are intended to come together during the project, with traits from each approach being stacked into a single pine tree to meet the final program goal. In total, under ARPA-E project support, UF, ArborGen and the University of California, Berkeley's Joint BioEnergy Institute (JBEI) have generated 10,000 transgenic loblolly pines using genes identified through these three strategies.

For strategy 1, UF investigated the process by which stimulating the tree with treatments of methyl jasmonate increases the amount of turpentine in harvested pine and identified the genetic controls behind high terpene accumulation. UF analyzed the global gene responses in pine to chemical stimulation and used association genetics to select the most promising gene candidates to test in transgenic trees.

In parallel for strategy 2, JBEI discovered a novel metabolic pathway from C5 sugars to terpenes in bacteria. This pathway is more direct and energy efficient than the current terpene biosynthesis pathway and also circumvents feedback regulatory mechanisms. UF/ArborGen transformed the key gene and observed that the bacterial gene functioned in pine. Young (18-month) transgenic pine trees expressing the bacterial gene accumulated significantly more terpenes than wild type pines.

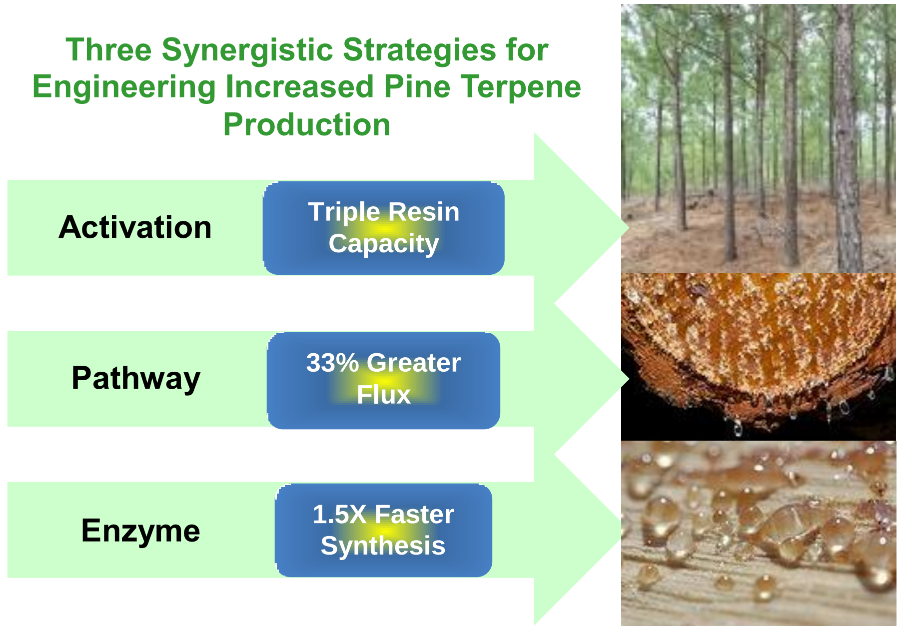


Figure 1. Schematic Depiction of the University of Florida's Technical Approach

Pine trees naturally produce a mix of terpene molecules. As part of strategy 3, JBEI identified genes from other plants that produced enzymes that preferentially synthesize terpene molecules with properties desirable for fuel uses, such as α-pinene. JBEI utilized various protein engineering strategies to improve the specificity and rate of activity of terpene synthase enzymes *in vitro*, and these gene candidates have been transformed into pine trees.

In total, UF and JBEI built 137 gene constructs, made up of individual or combinations of genes identified by the three strategies. These constructs include gene combinations from each strategy predicted to act most synergistically to produce and accumulate terpenes. The oldest of the transgenic trees developed under this project are now 3 years old, and so far the most promising lines show roughly a doubling of wood terpene concentration at the sapling stage. To allow processing of 10,000 trees in a timely manner, the National Renewable Energy Laboratory (NREL) developed high throughput analytical techniques based on gas chromatography and pyrolysis molecular beam mass spectrometry to rapidly quantify terpenes in wood samples. While not all the transgenic trees have been characterized yet as they continue to grow, the project’s model for terpene accumulation suggests that the most promising lines so far could yield 12% terpene once those trees have fully matured.

In parallel with developing the transgenic pines, UF has also continued to work on chemical stimulation as a route to increase terpene content in the near term with an industrial partner, Ingevity Corporation. Ingevity supplies pine-based chemicals used in the manufacture of products for the asphalt paving, oil exploration and production, agrochemicals, adhesives, lubricants, and printing inks industries.

PATHWAY TO ECONOMIC IMPACT

At the end of this project, UF will have produced transgenic pine saplings up to four years old and quantified the improved production of terpenes. The team will also have completed a techno-economic analysis (TEA) of the commercial potential for an alternative approach of treating trees chemically, just prior to harvesting, to increase the yield of terpenes. Because the market for biofuels has been affected by low oil prices and regulatory uncertainty, the first markets are expected to be in specialty chemicals. The newly developed methods of chemical stimulation and mechanical tapping of existing stands of southern pines show promise for a first market entry with these chemicals. The TEA indicates that this technology would create $1,500/acre of gross economic activity and $150/acre of annual net income for land owners while the trees are growing. This ongoing income stream and terpene production would provide economic optionality to these owners that is uncorrelated with the housing lumber market, while simulataneously maintaining sufficient terpene supply for the speciality chemicals market.

LONG-TERM IMPACTS

The UF project has demonstrated the practical potential for identifying pathways and using transgenic approaches to increase desired chemical production from plants, as the pathway identified by JBEI would be expected to increase levels of terpenes in most plants.

The longer term commercial objectives of the engineered trees are: to triple terpene feedstock per tree, to address supply concerns for the manufacture of the aforementioned specialty chemicals in the U.S., to increase the value of this agricultural product for land owners and pulp and paper mills, and to provide increased employment and economic development in rural areas of the southern U.S.

Ultimately, such approaches could make domestic crops the source of fuel precursors for the domestic production of aviation and diesel biofuels, enabling large-scale production of replacements for petroleum-based fuels. A concrete example based on the TEA would be the development of a new renewable fuel source from pines at a cost of <$50/BOE, yielding 100 million gallons of fuel on an area (10,000 hectares) smaller than Washington, DC.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of September 2015, the University of Florida team's project has generated 1 invention disclosure to ARPA-E. The team has also published the scientific underpinnings of this technology extensively in the open literature. A list of publications is provided below:

Harman-Ware, A.E., Sykes, R. Peter, G.F., Davis, M., 2016. Determination of terpenoid content in pine by organic solvent extraction and fast-GC analysis. *Frontiers in Energy Research* 4:2 doi: 10.3389/fenrg.2016.00002

Kirby, J. et al. (2014). Use of nonionic surfactants for improvement of terpene production in *Saccaromyces cerevisiae*. *Applied and Environmental Microbiology.* 80: 6685-93.

Kirby, J. et al. (2015). Enhancing Terpene Yield from Sugars via Novel Routes to 1-Deoxy-D-Xylulose 5-Phosphate *Appl. Environ. Microbiol.* 81: 130-138.

Suseata, A., Peter, G.F., Hodges, A.W., Carter, D.R., 2014. Oleoresin tapping of planted slash pine (*Pinus elliottii Engelm*. var. *elliottii*) adds value and management flexibility to landowners in the southern United States. *Biomass and Bioenergy* 68: 55-61.

Westbrook, J. et al. (2014). Discovering candidate genes that regulate resin canal number in Pinus taeda stems by integrating genetic analysis across environments, ages, and populations. *New Phytologist. 199: 89-100.*

Westbrook, J.W., Walker, A.R., Neves, L.G., Munoz, P., Resende Jr., M.F.R., Neale, D.B., Wegrzyn, J.L., Huber, D.A., Kirst, M., Davis, J.M., Peter, G.F., 2015. Discovering candidate genes that regulate resin canal number in *Pinus* stems by integrating association genetics and QTL analysis across environments, ages, and populations. *New Phytologist* 205: 627-641.

GRID OPERATIONS

Overview:

Ideally, the electric power grid would allow power distribution companies to buy the lowest cost electricity available and distribute it to their customers. Unfortunately, today's electric power grid is "congested"—the power lines needed to deliver the lowest-cost power are limited in the amount they can carry. As a result, distribution companies often have to buy higher-cost power that is available through other grid pathways and consumers pay higher prices as a result.

Addressing these problems will support greater integration of renewable power, as these resources are variable, and are often in different locations relative to conventional generation, or far from population centers.

One solution, building substantial additional transmission infrastructure, would be very costly. An alternative approach is to use the existing infrastructure more effectively. ARPA-E's GENI program (2011) addressed this possibility through innovative projects in power-flow-control and grid control architectures.

Each area has demonstrated new approaches, and through technology-to-market activities, has demonstrated sufficient value to engage power utilities in cooperation, support for field demonstration, and some early installations.

Examples of some projects that have active engagement with power utilities are:

- Smart Wires (GENI) – Distributed Power Flow Control Using Smart Wires for Energy Routing
- Varentec (GENI) – Compact Dynamic Phase Angle Regulators for Transmission Power Routing
- Boston University (GENI) – Transmission Topology Control for Infrastructure Resilience to the Integration of Renewable Generation
- Autogrid (GENI) – Highly Dispatchable and Distributed Demand Response for the Integration of Distributed Generation

DEVELOPING TECHNOLOGY TO IMPROVE ELECTRICITY TRANSMISSION CAPACITY

Updated: February 24, 2016

PROJECT TITLE: Distributed Power Flow Control Using Smart Wires for Energy Routing
PROGRAM: Green Electricity Network Integration (GENI)
AWARD: $3,977,745
PROJECT TEAM: Smart Wires (Lead); Carnegie Mellon University; PowerWorld Corporation; Georgia Tech Research Corporation; Electrical Distribution and Design, Inc.; Innoventor, Inc.; New Potato Technology, Inc.
PROJECT TERM: April 2012 – September 2014
PRINCIPAL INVESTIGATOR (PI): Frank Kreikebaum

TECHNICAL CHALLENGE

The electric transmission grid faces severe challenges over the next several decades due to the changing nature of electric demand, rapidly increasing renewable generation penetration, retirement of conventional generation and an aging infrastructure. These challenges have led to increased congestion on the electricity grid and higher costs to meet reliability standards, which are required to avoid blackouts that can cause billions of dollars in economic losses annually. A grid operator's limited ability to control the flow of power through the transmission grid is a major factor limiting performance, as it requires the grid operator to be extremely cautious and set line loading limits significantly below the actual line capacity. This inefficient utilization of capital-intensive grid infrastructure results in increased energy losses, unnecessary and expensive over-build of the transmission system, and impedes the integration of distributed and renewable electricity generation.

TECHNICAL OPPORTUNITY

Power flow control hardware has traditionally been approached as in-line components that are fully rated for both the large currents and the high voltages of transmission lines. The high costs of developing and manufacturing such units, and the footprint and cost of installing and maintaining them have been significant barriers to cost-effective approaches to power flow control. The Smart Wires team based their technology on an alternative concept, originally invented at Georgia Institute of Technology, in which the hardware inductively modifies the current flow using clamp-on magnetic core-based devices distributed along the transmission line.

INNOVATION DEMONSTRATION

Smart Wires, formerly known as Smart Wire Grid, developed a solution for controlling power flow within the electric grid based on a Distributed Series Reactance (DSR) device, now called the PowerLine Guardian™. The PowerLine Guardian devices clamp on to existing transmission line conductors and allow the operator to increase the line impedance on command using wireless communication control. The self-powered controller acts like a valve on the power line; it is capable of redirecting power to underutilized power lines in a meshed network for greater efficiency and overload prevention.

Figure 1. TVA personnel reviews installation procedures before installing the PowerLine GuardianTM on the line

Under ARPA-E funding, Smart Wires was able to move from prototype to a field-ready unit in under a year. They developed a control system, electrical and mechanical design, the magnetic core, and packaging for extreme environments. Following laboratory testing under worst-case environmental and operational conditions, they successfully demonstrated units in a Tennessee Valley Authority (TVA) field trial—100 units deployed on a 161 kV transmission line (Knoxville, TN). The low-cost installation of the devices, and the fact that they do not require integration into substations, enabled the rapid field tests.

The project team developed multiple power system models to identify opportunities to deploy Smart Wires technology and compare those opportunities to conventional network investments. Preliminary system simulations conducted during the project indicate that these devices could potentially increase overall system utilization by more than 30%. This would allow utilities to significantly increase the capabilities of their existing infrastructure while safely deferring new transmission investment, resulting, in some cases, in a present value savings of over 80% relative to conventional transmission reinforcements. Beyond overload prevention and congestion management, other applications such as phase balancing, also appear promising.

Since the end of the ARPA-E project, the team has also expanded the capabilities of their system-level control software, called PowerLine CommanderTM and developed new types of power flow controllers which are able to both push power away from an over utilized line or incent flow through an underutilized line.

PATHWAY TO ECONOMIC IMPACT

Towards the end of the project, Smart Wires appointed a new CEO and leadership team to advance the commercialization process. The company has raised roughly $60 million in three rounds of private-sector funding.

Because utilities must be extremely risk averse, the sales cycle for new technology is long, resulting in significant financial difficulties for small companies bringing new products to this market. Smart Wires has addressed these challenges through a carefully crafted go-to-market strategy and the development of additional product lines. The ARPA-E grant was critical in providing Smart Wires the funding it needed to begin commercialization of its first product.

LONG-TERM IMPACTS

Smart Wires' power flow control devices are an early success story in demonstrating the potential to increase overall grid transmission capacity use by improving the utilization of existing lines. Field testing and validation of the Smart Wires devices is ongoing, and will provide industry context not only for the Smart Wires approach, but also will allow field tests of power flow control as an operational approach. This, along with parallel developments of planning and control software, will provide the foundation for power flow control to become a key player in the modernization of the electric power grid.

The final impact on the transmission system will depend on widespread acceptance and adoption of power flow control as a viable planning and operational approach. The expected benefits include reduced need for expensive new transmission infrastructure, improved grid reliability and resiliency, reduced congestion and ability to integrate higher penetrations of renewable power sources. The value of these benefits will be further quantified through continued studies, testing, and evaluation.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the Smart Wires team has generated two invention disclosures to ARPA-E. The team has also published the scientific underpinnings of the technology extensively in the open literature. A list of publications is provided below:

Hug, G., "Generation cost and system risk trade-off with corrective power flow control," in *Communication, Control, and Computing (Allerton), 2012 50th Annual Allerton Conference*, pp.1324-1331, 1-5 Oct. 2012.

Lowe, Shultz, Grant, and Lambert, "Smart Control of Transmission", *Transmission and Distribution World,* pp. 24-28, Apr. 2013.

Mohammadi, J.; Hug, G.; Kar, S., "On the behavior of responsive loads in the presence of DFACTS devices," in North American Power Symposium (NAPS), 2012, pp. 1-6, 9-11 Sept. 2012.

Perez, R.C., Oliveira, G.C., Pereira, M.V., Falcao, D.M., Kreikebaum, F, Ramsay, S.M, "FACTS and D-FACTS: The Operational Flexibility Demanded by the Transmission Expansion Planning Task with Increasing RES," CIGRE US National Committee 2014 Grid of the Future Symposium, Aug. 2014.

Ramsay, S., Couillard, J., Melcher, J., Thomas, C., Kreikebaum, F., "Deploying Power Flow Control to Improve the Flexibility of Utilities Subject to Rate Freezes and Other Regulatory Restrictions," CIGRE US National Committee 2013 Grid of the Future Symposium, Aug. 2013.

GRID MODERNIZATION WITH POWER FLOW CONTROLLER

Updated: April 28, 2016

PROJECT TITLE: Dynamic Power Flow Controller	
PROGRAM: Green Electricity Network Integration (GENI)	
AWARD: $4,025,951	
PROJECT TEAM: Varentec (Lead); Electric Power Research Institute (EPRI); Georgia Tech Research Corporation; SPX Transformer Solutions (Waukesha Electric Systems)	
PROJECT TERM: January 2012 to April 2016	
PRINCIPAL INVESTIGATOR (PI): Dr. Deepak Divan	

TECHNICAL CHALLENGE

The challenges of improving grid reliability, bolstering infrastructure resiliency, and enabling increasing utilization of renewable energy sources while minimizing costs require more efficient utilization of existing power transmission networks. The ability to optimize the routing of power through existing lines would be a significant step forward. However, traditional technology solutions for power flow control have been too slow, too expensive, and insufficiently flexible. Dynamic power flow control, which would allow real-time redirection of current among the power lines, offers opportunities for dramatically enhancing grid utilization. However, implementation is extremely challenging, as such controllers must operate at high voltages and currents, under extreme environmental conditions, and provide reliability under emergency conditions, such as power surges, that severely stress electronic components. The development of highly performing, low-cost dynamic power flow controllers would enable new energy markets, improved integration of renewable resources, and reduce the need for expensive and often controversial new transmission lines.

TECHNICAL OPPORTUNITY

Recent advances in the power electronics field created new concepts for power flow control. Specifically, one such innovation is the design of power flow control systems using “fractionally rated converters” which are designed to inject a series voltage into transmission lines using power electronics that are rated for only a small fraction of the full system current and voltage. A relatively small series voltage (e.g. ~10% of nominal voltage) of controlled phase, injected in this way can change the flow in the line over a wide range (e.g. ~100%) and can even reverse the direction of power flow if required. Fractionally rated converter-based system design approaches could enable reductions in the size and rating of electronic components required and reduce overall cost of the system while maintaining higher reliability. A smaller rating also leads to lower losses, and subsequently to a smaller thermal management system, as less heat needs to be dissipated to ambient. If successful, such a power flow control device could, for example, be used to limit the power flow in an otherwise overloaded line. The electricity would be forced to find an alternative path through under-utilized lines, resulting in more efficient use of the entire network.

INNOVATION DEMONSTRATION

The ARPA-E award supported Varentec’s research and development of a low-cost, fractionally-rated, power flow control device that uses controlled series voltage injections in series with transmission lines to control power flows. The project goal was the prototype demonstration of a 1MVA power flow controller for electric utility distribution systems (12.47 kV). This target makes it possible to verify the power flow control concepts on live utility distribution circuits, while avoiding the high cost of developing and testing experimental equipment for transmission system voltage levels.

The schematic of the device is shown in Figure 1. Its three fractionally-rated direct AC converters are attached to low voltage taps on the secondary of a transformer. The power electronics converters are comprised of an AC chopper circuit that can be rated at only a fraction of the total line power, typically selected to be 10-20% of the total system rating.

The Varentec project team considered several possible configurations for the power flow control device. Tradeoffs involving system cost, ease of installation and maintenance, size, efficiency, and scalability to high voltages were all considered carefully. In the final design, the power electronics are connected near the neutral of a power transformer (as shown in Figure 1). This greatly reduces the insulation requirements and lowers the overall cost of the equipment. This design also enables installation of the device as a retrofit (connected to the neutral point of an existing transformer) or as a new-build device in which the fully rated transformer is included.

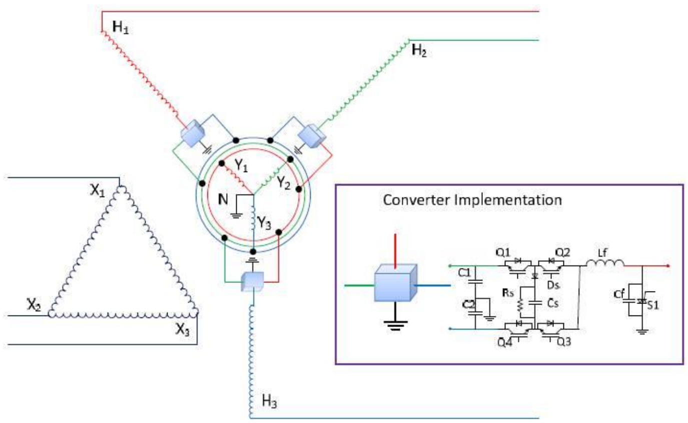


Figure 1. Schematic of the system design. Fractionally-rated converters are connected to low voltage taps on the secondary windings of the power transformer (as shown in the center of the figure). The configuration enables controlled injection of a series voltage on each phase (using voltages from the other two phases as inputs). External control signals are applied at the bases of the four transistors in each converter. The converter outputs (Vconv) are added to the original phase voltages creating phase shifts on each of the three outputs, which result in power flow changes. The delta primary winding for the transformer is also illustrated

The Varentec team built three fully functional power flow controllers that were tested and operated in a specially-built 12.47 kV 1MVA meshed power network testbed at Georgia Tech's National Electric Energy Testing Research and Applications Center (NEETRAC) utility test facility. Technical components of the design included a custom transformer, three AC chopper circuit based power converters, a novel passive cooling system integrated into the transformer structure, and controls to ensure the device would operate with high reliability in the field, despite always changing grid conditions. Controlled voltage output from the converters is injected into the low voltage end of the transformer's secondary windings. Challenges the team addressed during the project included the design of sequences for system start-up and shutdown, fail-normal functionality enabled by a series switch located around the entire system, and a full passive cooling system with no moving parts. In early laboratory testing, the team demonstrated the ability to inject phase-controlled voltages up to 250 VAC (about 3.5%) in series with a 3-phase, 12.47 kV line carrying 1 MVA.

Following successful laboratory tests, one of the prototype power flow controllers was installed in the field on the Southern Co. power system in Georgia, where the prototype provides a controlled inter-tie between two, previously-isolated, 12.47 kV radial distribution feeders. Thus far, the prototype power flow controller has been tested over a 600 kVA range and startup/shutdown sequences have been verified. In open loop testing, line power has been controlled from -376 kW to 224 kW. Ultimately, the controller could be used by utilities to balance the demands placed on transformers at substation transformers providing power to different feeders. This installation test is particularly significant because it demonstrates how low-cost power electronic devices can be used to achieve mesh interconnection of radial feeders. Meshing of the distribution system gives consumers access to multiple power sources through multiple paths, making it possible to maintain service to many customers even under fault conditions. The new technology also presents new challenges, such as providing protection for a network with multiple power sources.

PATHWAY TO ECONOMIC IMPACT

Varentec's power flow controller has been successfully demonstrated at distribution power levels, where the potential value could be created by enabling the mesh interconnection of multiple, previously isolated, radial distribution feeders. The value of such a scheme includes possible savings through deferred distribution system upgrade costs, and also includes intangibles that are difficult to evaluate in dollar terms, such as improved availability of service through reduced outages.

Varentec's approach, if successfully scaled up for application at transmission level voltage and power levels, could provide considerable value in a variety of transmission system applications for controllability of a meshed grid, even under current regulatory and market practices. At the simplest level, the ability to change real and reactive power flows in a specific transmission or sub-transmission line can mitigate congestion by allowing power flow on alternate paths where there is spare capacity. Simulations of power system operations have indicated that the ability to change power flows under a contingency, such as a line trip, could have a dramatic impact on the need to build additional system capacity.

LONG-TERM IMPACTS

The ability to dynamically control power flows on the grid can enhance asset utilization by adaptively reconfiguring the transmission system according to changing conditions. Previous system simulations conducted at Georgia Tech indicated that such enhanced capability can reduce the need for new asset construction, potentially reducing transmission and distribution investments by as much as 80%.[6,7]

Over time, implementation of power routing capability on the grid will improve the economic efficiency of wholesale markets. The policies and regulations underlying electricity markets today were written with the assumption that power cannot be stored or routed. With the new capabilities enabled by power flow devices such as Varentec's CD-PAR, power system optimization will become much more efficient and operators will be empowered with new options to ensure reliability. This could have profound effects on the choices of market participants and lead to dramatically reduced costs.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of April 2016, the Varentec team has reported 2 invention disclosures to ARPA-E and 2 U.S. Patent and Trademark Office (PTO) patent applications. The team has also published the scientific underpinnings of this technology in two articles:

"Design Considerations and Experimental Results for a 12.47-kV 3-Phase 1 MVA Power Router." R P Kandula, A. Prasai, H. Chen, R. Mayor, F. Lambert, T. Heidel, C. Schauder, and D. Divan, ECCE 2015.

"Compact Dynamic Phase Angle Regulator For Power Flow Control," A. Prasai, R P Kandula, R. Moghe, T. Heidel, C. Schauder, and D. Divan, ECCE 2015.

[6] D. Das, F. Kreikebaum, D. Divan, "Reducing transmission investment to meet Renewable Portfolio Standards using Smart Wires," IEEE PES Transmission and Distribution Conference and Exhibition 2009/2010.

[7] F. Kreikebaum, D. Das, and D. Divan, "Reducing transmission investment to meet Renewable Portfolio Standards using Controlled Energy Flows," in Conf. Proceed. of ISGT 2010, pp. 1-8, Jan. 2010.

ADVANCED POWER FLOW TOPOLOGY CONTROLS FOR THE GRID

Updated: October 28, 2015

PROJECT TITLE: Transmission Topology Control for Infrastructure Resilience to the Integration of Renewable Generation	
PROGRAM: Green Electricity Network Integration (GENI)	
AWARD: $2,361,591	
PROJECT TEAM: Boston University (Lead); Newton Energy Group; Northeastern University; AIMMS; PJM Interconnection; Polaris Systems Optimization; The Brattle Group; Tufts University	
PROJECT TERM: April 2013 – March 2016	
PRINCIPAL INVESTIGATOR (PI): Dr. Pablo Ruiz	

TECHNICAL CHALLENGE

The primary objectives of electric market and grid operators are to ensure reliable operations and minimize the cost of providing electricity by purchasing and delivering this energy source from the lowest-cost generators to customers. However, these generators are not always ideally located to service customer needs. As a result, utilities must purchase electricity from higher-cost generators and/or curtail renewable generation, to levels at which transmission lines do not exceed their thermal limits, causing reliability problems and network congestion. Purchasing (or dispatching) more expensive electricity sources due to transmission congestion leads to multi-billion dollar congestion costs annually in the U.S. Active management of transmission and distribution is needed to enable more low-cost renewable generation sources to penetrate the electric market, improve grid resiliency and reliability, and reduce electricity costs for end users.

TECHNICAL OPPORTUNITY

Today, flows in the electric grid are typically managed by adjusting the power drawn from different generators (i.e. generation dispatch) and/or modulating electricity demand (i.e. Demand Response), assuming for the most part an uncontrollable transmission system. Transmission network changes at present are created by switching specific lines in and out of service. Network flexibility is usually not exploited in optimizing electricity supplies and demands because the procedures to determine good configurations are complex and the analysis and implementation processes are slow. Advances in applied mathematics have created new methods for identifying solutions to the network configuration problems in the form of fast optimization algorithms that can be implemented with modern computational capabilities.

INNOVATION DEMONSTRATION

Boston University's (BU) topology control technology is designed to help grid operators actively manage power flows and integrate renewables by switching entire power lines in and out of service in coordination with traditional management of generators and demand. The topology control technology identifies transmission lines to be switched to mitigate network congestion and improve system reliability.

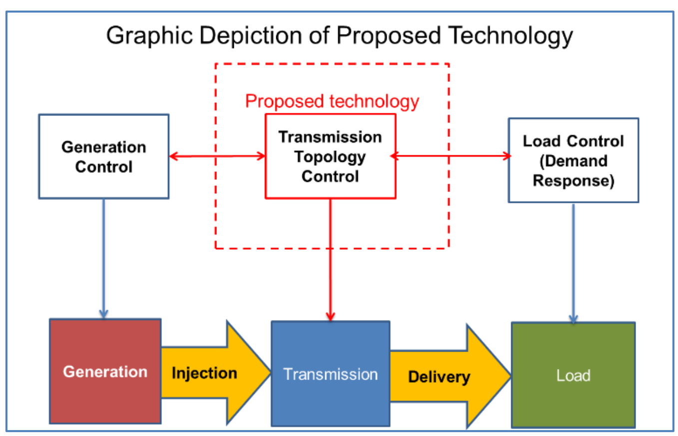


Figure 1. Demonstrates the transmission of Boston University's power flow technology

Identifying beneficial reconfigurations in real-time is difficult due to the complexity of even a moderate-sized utility grid. The BU research team has made breakthroughs by drawing on their previous academic research in fast, computationally tractable algorithms. The team's topology control technology uses fast optimization algorithms taking advantage of sensitivity information from the system. Their algorithms identify incremental network topology modifications on a time scale that enables their implementation to improve reliability and decrease congestion costs.

BU researchers worked on detailed, operational network models demonstrating the ability to generate solutions on an operationally relevant time scale (~5 minutes), the potential to save up to 50% in congestion costs in some systems under average historical grid conditions, the ability to reduce renewable curtailments by 40% in a high-renewables scenario, and the capability to relieve significant overloads even under peak demand conditions.

PATHWAY TO ECONOMIC IMPACT

The BU team has received additional funding from the Massachusetts Clean Energy Commission, and is working to market their Topology Control Algorithms (TCA) technology through established consulting entities that have the knowledge and relevant personnel to be able to market the TCA systems.

The team is also working with industry stakeholders to integrate topology control into grid operations decision making, focusing first on improving established utility/International Organization for Standardization (ISO) business processes that do not require market rule modifications. Aside from market rules, the team will work with industry stakeholders on addressing hurdles to topology control, such as multi-party coordination and equipment protection. The team has formed a software company to develop the commercial decision support tool.

LONG-TERM IMPACTS

The BU team has demonstrated that large-scale topology control is tractable. There are many uses for this type of software (from intra-day dispatch to outage coordination to system planning). It remains to be seen what particular application generates traction first. Adoption of the topology control technology in some electric grid decision making processes may require changes to the day-ahead and real-time electricity market rules and/or procedures, while other processes already deploy topology changes to a limited extent. Market use in these processes may occur first and proceed in parallel with developments in market rules and/or procedures.

PUBLICATIONS

The BU team has published scientific underpinnings of the technology extensively in the open literature. A list of publications is provided below:

P. A. Ruiz, J. Foster, A. M. Redkevich and M. C. Caramanis, "*Topology Control Algorithms (TCA): Economic and Corrective Applications*", 2012 FERC Conf. Improving Market Efficiency, Docket AD10-12-003, June 2012.

A. Rudkevich, "*A Nodal Capacity Market for Co-optimization of Generation and Transmission Expansion*", Proc. 50th Allerton Conference on Communications, Control and Computing, October 2012.

P. A. Ruiz, A. Rudkevich, M. C. Caramanis, E. Goldis, E. Ntakou and R. Philbrick, "*Reduced MIP formulation for transmission topology control*", Proc. 50th Allerton Conference on Communications, Control and Computing, October 2012.

M. Stanković and A. T. Sarić, "*Fast Assessment of Eigenvalue Sensitivities to Topology Changes and Injection Perturbations*", Proceedings of IEEE PowerTECH Conference, Session "Loads and Flows Modeling", Paper A5494AS, Grenoble, France, June 2013.

P. A. Ruiz, M. C. Caramanis, J. M. Foster, E. Goldis, X. Li, C. R. Philbrick, A. M. Rudkevich, R. D. Tabors, T. B. Tsuchida, "*Advances in Topology Control Algorithms (TCA)*", 2013 FERC Conf. Improving Market Efficiency, Docket AD10-12-004, June 2013.

P. A. Ruiz, M. C. Caramanis, E. Goldis, B. Keshavamurthy, X. Li, M. Patel, C. R. Philbrick, A. M. Rudkevich, R. D. Tabors, T. B. Tsuchida, "*Transmission topology control for system efficiency – Simulations on PJM Real Time Markets*," presented at 2013 IEEE PES General Meeting, Super Session on Transmission System Efficiency and Reliability Improvements, Vancouver, BC, July 2013

A. Rouhani and A. Abur, "*Distributed Implementation of an augmented state dynamic state estimator*", 2013 North American Power Symposium, September 2013.

A. Rouhani and A. Abur, "*Improving Performance of Dynamic State Estimators under Unknown Load Changes*", 2013 IEEE PES General Meeting, July 2013.

S. D. Đukić, A. T. Sarić and A. M. Stanković, "*Approximate Bisimulation-Based Reduction of Power System Dynamic Model with Application to Transient Stability Analysis*", North American Power Symposium (NAPS), Kansas State University, USA, September 22-24, 2013.

E. A. Goldis, X. Li, Michael C. Caramanis, Bhavana Keshavamurthy, Mahendra Patel, Aleksandr M. Rudkevich, A. Ruiz, P. "Applicability of Topology Control Algorithms (TCA) to a Real-Size Power System", 51st Allerton Conference on Communications, Control and Computing, October 2013.

E. A. Goldis, M. C. Caramanis, C. R. Philbrick, A. M. Rudkevich and P. A. Ruiz, "*Security-constrained MIP formulation of topology control using loss-adjusted shift factors*", 47th Hawaii Int. Conf. System Science, January 2014.

P. A. Ruiz, M. C. Caramanis, E. Goldis, B. Keshavamurthy, X. Li, C. R. Philbrick, A. M. Rudkevich, R. D. Tabors, T. B. Tsuchida "*Topology control algorithms (TCA) – Simulations in PJM with AC Modeling*," 2014 FERC Conf. Improving Market Efficiency, Docket AD10-12-005, June 2014.

A. M. Rudkevich, M. C. Caramanis, E. A. Goldis, X. Li, C. R. Philbrick, P. A. Ruiz, R. D. Tabors, and T. B. Tsuchida, "*Advanced Methods in Transmission Topology Control Optimization and their Applications*", 2nd International Symposium on Energy Challenges & Metrics, Aberdeen, Scotland, UK, August 19, 2014.

P. A. Ruiz, X. Li, T. B. Tsuchida, "*Transmission Topology Control - Curtailment Reduction through System Reconfiguration*", UVIG 2014 Fall Technical Workshop, October 2014.

P. A. Ruiz, M. C. Caramanis, E. Goldis, D. Hislop, B. Keshavamurthy, X. Li, D. Moscovitz, C. R. Philbrick, A. M. Rudkevich, R. D. Tabors, and T. B. Tsuchida, "*Topology Control Algorithms: Applications for Market Efficiency Improvements and Overload Relief*", 2014 IEEE PES General Meeting Super Session on Grid Operations, National Harbor, MD July 30, 2014.
J. Goldis, X. Li, M. Caramanis, A. Rudkevich and P. Ruiz presented, "*AC-Based Topology Control Algorithms (TCA) – A PJM Historical Data Case Study*" at HICSS 48 in Hawaii in January 2015.

P. A. Ruiz, M. C. Caramanis, E. Goldis, D. Hislop, B. Keshavamurthy, X. Li, D. Moscovitz, C. R. Philbrick, A. M. Rudkevich, R. D. Tabors, T. B. Tsuchida, "*Topology Control Algorithms (TCA) – Simulations in PJM Day Ahead Market and Outage Coordination*," 2015 FERC Conf. Improving Market Efficiency, Docket AD10-12-006, June 2015

A. M. Rudkevich, M. C. Caramanis, E. Goldis, X. Li, P. A. Ruiz, R. D. Tabors, "*Preserving Revenue Adequacy in FTR Markets with Changing Topology*," 2015 FERC Conf. Improving Market Efficiency, Docket AD10-12-006, June 2015

P. A. Ruiz, J. Chang, "*Transmission Topology Control – Applications to Outage Scheduling, Market Efficiency and Overload Relief*," presented at WIRES Summer Meeting, Boston, July 2015

A. M. Rudkevich, M. C. Caramanis, E. Goldis, X. Li, P A Ruiz, R. D. Tabors, "*Financial Transmission Rights in Changing Power Networks*," at HICSS 49 in Hawaii in January 2016.

IMPROVING THE INTEGRATION OF RENEWABLES ON THE GRID

Updated: April 26, 2016

PROJECT TITLE: Highly Dispatchable and Distributed Demand Response for the Integration of Distributed Generation
PROGRAM: Green Electricity Network Integration (GENI)
AWARD: $3,465,385
PROJECT TEAM: AutoGrid Systems (Lead); Columbia University; Lawrence Berkeley National Laboratory
PROJECT TERM: January 2012 – March 2014
PRINCIPAL INVESTIGATOR (PI): Amit Narayan

TECHNICAL CHALLENGE

The primary objective for grid operators is to provide reliable electricity at minimum cost by purchasing electricity from the lowest cost generators and delivering it to customers. However, the configuration of the transmission lines that deliver power from the generators is often not well matched to customer locations. As a result, overloaded transmission lines can approach their thermal limits, causing network congestion and forcing utilities to purchase electricity from higher cost generators and/or curtail renewable generation. Purchasing (or dispatching) more expensive electricity sources due to transmission congestion is estimated to cost an additional $5 to $10 billion per year in the U.S. This problem is expected to worsen with the changing characteristics of electrical demand and rapidly increasing variable renewable generation penetration in the electricity grid. New technologies that manage the existing resources of the grid more effectively are needed to provide the cleanest and most cost-effective approach to using our power generation resources.

Temporarily reducing the demand for electricity to avoid congestion, often called Demand Response (DR), is a powerful tool that grid operators can use to help improve reliability and reduce cost. Historically, demand response has largely been used only during anticipated "events," with planning a day in advance, and with little or no matching of the controls to different customers, different regions, or changes in conditions over time. Furthermore, historically only large electricity customers (100 kilowatts and above) were able to participate in demand response programs because of the expense and specialized hardware and communications technologies that were required.

Greater ability to tailor demand response requests based on individual customer characteristics, and greater forecasting precision are needed to fully unlock the potential of demand response technologies. Indeed, recent studies by LBNL[8] and RMI[9] show that DR could be more cost-effective than increasing spinning reserves or adding grid-scale storage to address

Figure 1. DROMS System Features

[8] David S. Watson, Nance Matson, Janie Page, Sila Kiliccote, Mary Ann Piette, Lawrence Berkeley National Labs, "*Fast Automated Demand Response to Enable the Integration of Renewable Resources*", Report LBNL-5555E, June 2012.

[9] Peter Bronski, Mark Dyson, Matt Lehrman, James Mandel, Jesse Morris, Titiaan Palazzi, Sam Ramirez, Hervé Touati. Rocky Mountain Institute (RMI), "*The Economics of Demand Flexibility*", August 2015.

contingency shortfalls or to accommodate large-scale renewable energy penetration.

TECHNICAL OPPORTUNITY

The deployment of utility advanced metering infrastructure (AMI) and other communications-enabled sensors in recent years has enabled utilities to collect far more detailed information on both the operation of their systems and electricity use profiles. For the first time, utilities can collect and analyze data on individual customer electricity use in near real-time. Separately, advances in software tools to collect, store, and analyze large datasets[10] and cost-effective, large-scale, commercial cloud computing infrastructures have become more widely available. These new tools are facilitating the development of far more sophisticated data analytics and forecasting applications across a wide range of different industries, and have led to rapid advances in many areas of computer science including machine learning and optimization.

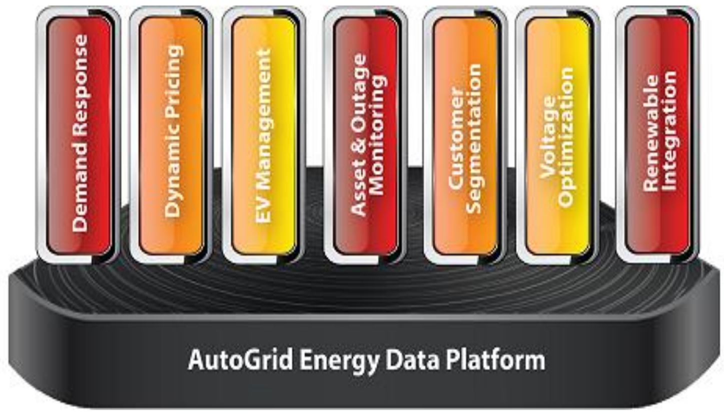


Figure 2. DROMS Energy Data Platform Services

The advances described on the previous page are enabling the development of a wide range of new utility-specific data analytics applications. The research community has been exploring new approaches to forecasting and dispatch of new distributed energy resources, including smart thermostats, electric vehicles, electricity storage installations, etc.

INNOVATION DEMONSTRATION

Under ARPA-E support, AutoGrid, in conjunction with Lawrence Berkeley National Laboratory and Columbia University, designed, developed, and deployed a scalable software-as-a-service (SaaS) demand response optimization platform known as the Demand Response Optimization and Management System – Real-Time (DROMS-RT). The goal of the DROMS-RT software platform was to build bottom up demand response forecasts at the granularity of individual customers in presence of dynamic pricing signals or other demand response signals in near real-time. With this information, the system was also developed to manage the optimal dispatch of DR resources across large portfolios of heterogeneous demand response programs (with different enrolled customers, utility business rules, time horizons, etc.).

Achieving high forecast precision for millions of individual customers in extremely short timeframes required the team to leverage recent advances in machine learning, data mining, and robust optimization. During the ARPA-E project, AutoGrid and its partners evaluated a wide range of different potential forecasting methods based on segmenting customers into different classes based on their historical response to different DR events. They developed methods to enhance the forecasts by the collection of periodic electricity usage data at individual customer locations, and to predict changes in customer load profiles using load time series of individual customers. The resulting system generates individual customer load usage and load shed forecasts (with associated forecast error distributions). AutoGrid also included compatibility with real-time DR signaling to customer devices (including thermostats and electric vehicle charging stations), and included the use of data from these devices to further increase the precision of the DROMS-RT individual customer forecasts. The system is designed to provide individual DR signals that can be sent to customers based on utility needs and the calculated individual customer demand response forecasts.

The AutoGrid team demonstrated a highly parallel machine learning engine capable of processing more than 1 million forecasts on a rolling basis every 10 minutes, performance significantly beyond industry expectations using most existing utility demand response software applications. The team also demonstrated the tool's ability to manage many different heterogeneous demand response programs. This helps grid operators better manage unpredictable demand

[10] Such as Hadoop (http://hadoop.apache.org) and NoSQL database like HBase (http://hbase.apache.org).

and supply fluctuations in short time-scales, making power system operations more efficient and cost-effective for both utilities and electricity consumers.

PATHWAY TO ECONOMIC IMPACT

AutoGrid is a start-up company that was incorporated just before obtaining its ARPA-E support, to develop the DROMS platform.

AutoGrid achieved significant initial traction with utility customers during their ARPA-E project. The platform was used to deploy commercial DR programs for more than 70K customers during field tests and early commercial deployments with various clients. DROMS-RT is expected to provide significant reduction in the cost of operating demand response and dynamic pricing programs in the U.S by eliminating up-front IT infrastructure costs for utilities, by dramatically reducing the end-point cost for customers, and by making the overall DR operations more efficient.

AutoGrid has raised $21.75 million in two rounds of follow-on funding from multiple investors. The company has more than 550 MW of Distributed Energy Resources (DERs) under contract, including Combined Heat and Power (CHP) units, energy storage systems, smart solar inverters, HVAC systems, commercial building lighting systems, Electric Vehicle (EV) chargers, smart thermostats, water heaters, pool pumps, and load control switches.

AutoGrid has more than 30 implementations across the globe. For example, Bonneville Power Administration (BPA) uses the AutoGrid DROMS-RT platform to implement fast and intelligent DR demonstrations, and DROMS serves as their DR command center. Recently, AutoGrid, in partnership with Eneco, deployed the first software-defined power plant in the Dutch electric grid using AutoGrid's software technologies. Other clients include Marin Clean Energy (where AutoGrid is pioneering market integration for the community choice model), Southern California Edison (where AutoGrid powers multiple EV pricing programs), Austin Energy (the first Bring Your Own Thermostat program), Portland General Electric (Behavioral DR for 70,000 customers), New Hampshire Electric Cooperative (Residential Internet of Things DR), City of Palo Alto Utilities (Behavioral Demand Response), Gexa (Texas market-based DR), and Hawaiian Electric (water heater DR to mitigate solar intermittency).

Since the end of its ARPA-E project, AutoGrid has been working to extend its cloud-based platform to enable it to manage and analyze large data sets for a range of additional energy applications. This platform, now known as AutoGrid's Energy Data Platform (EDP), is also designed to provide big-data analytics and predictive control services to third party applications.

In addition to success with customers, AutoGrid has received a number of awards. In 2016, AutoGrid was named a New Energy Pioneer by Bloomberg New Energy Finance and a winner of a Grid Edge Award by Greentech Media. In 2015, AutoGrid was named a World Economic Forum Technology Pioneer, a member of the Red Herring Top 100 North America, a member of the Cleantech 100, and a Smart Grid Company to Watch. AutoGrid was also named a 2015 finalist for both the Platts Global Energy Awards and the Circular Economy Awards. Previous awards include 2014 Green Product of the Year, Code_n Business Innovation Award at CeBIT 2014, and Greentech Media's Grid Edge 20.

LONG-TERM IMPACTS

New utility big data analytics applications such as the DROMS-RT system developed by AutoGrid promise to significantly improve the ability for utilities to optimize and control the grid and also promise to give customers more control over their energy usage and utility bills by providing them with up-to-date information on prices and real-time, grid-wide energy demand and supply conditions. These new tools could, over time, revolutionize data management and analysis practices for grid management and control applications.

Real-time granular demand response optimization and control specifically will also improve reliability and reduce costs by enabling full demand-side participation in electricity markets. This improved flexibility will become increasingly important as renewable resource penetrations grow over the next several decades.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the Autogrid team's project has generated 5 invention disclosures with ARPA-E and 5 U.S. non-provisional patent applications.

Patent Applications

"Determining Load Reductions In Demand Response Systems". (2012) U.S. Patent Application No. 14/345391. Washington, DC: U.S. Patent and Trademark Office.

"Identifying Operability Failure In Dr Assets". (2013) U.S. Patent Application No. 14/442904. Washington, DC: U.S. Patent and Trademark Office.

"Load Forecasting From Individual Customer To System Level Based On Price". (2012) U.S. Patent Application No. 14/345235. Washington, DC: U.S. Patent and Trademark Office.

"Scalable And Web-Based Dr Platform For Communication Of A Dr Signal Using A Network Server". (2012) U.S. Patent Application No. 14/345255. Washington, DC: U.S. Patent and Trademark Office.

"System And A Method For Optimization And Management Of Demand Response And Distributed Energy Resources". (2012) U.S. Patent Application No. 14/345248. Washington, DC: U.S. Patent and Trademark Office.

The AutoGrid team has also published journal papers and given conference presentations related to their work:

Publications

C. Abad; G. Iyengar, "A Near-Optimal Maintenance Policy for Automated DR Devices," in IEEE Transactions on Smart Grid, August 2015, vol.PP, no.99, pp.1-1.

M.A. Piette, S. Kiliccote, H. Junqiao, Dudley, "Field demonstration of automated demand response for both winter and summer events in large buildings in the Pacific Northwest", Journal: Energy Efficiency 2013.

S. Kiliccote, S. Lanzisera, A. Liao, O. Schetrit and M.A. Piette, "Fast DR: Controlling Small Loads over the Internet", ACEEE Summer Study on Energy Efficiency Buildings, August 2014.

V. Goyal, G. Iyengar and Z. Qiu, "Near-optimal execution policies for demand-response contracts in electricity markets," Decision and Control (CDC), 2013 IEEE 52nd Annual Conference on, Firenze, 2013, pp. 3697-3702.

V. Goyal, G. Iyengar, Q. Schwarz and S. Wang, "Optimal price rebates for demand response under power flow constraints," Smart Grid Communications (SmartGridComm), 2014 IEEE International *Conference on*, Venice, 2014, pp. 626-631.

POWER ELECTRONICS

Overview:

With the increasing use of sophisticated electric motors, appliances, energy storage, and renewable power generation, the amount of U.S. electric power that passes through power electronics devices is expected to increase from 30% today to 80% by 2030. The incumbent power electronics technology, based on silicon, is low cost and reliable but it is also inefficient and limited in performance.

ARPA-E has supported an evolving portfolio of innovative technologies in power electronics through its ADEPT (2010), Solar ADEPT (2011) and SWITCHES (2013) programs, as well as individual projects under OPEN 2009, 2012, and 2015.

The ADEPT and Solar Adept programs focused on innovations in integrated power conversion devices, and achieved significant advances that demonstrated the utility of wide band gap (WBG) semiconductors (specifically SiC and GaN) in increasing performance with cost-effective systems based on WBG devices.

The SWITCHES program was specifically designed to address key issues that have slowed uptake of power-electronics based on WBG semiconductors despite their energy efficiency and enabling benefits. The program is supporting projects in materials growth, device fabrication approaches, and device architectures with the goal of developing high-performance high-power devices that have functional cost parity with silicon power devices and provide superior system-level performance and cost.

Examples of some completed projects and some still underway are presented in the following documents:

- APEI (ADEPT) – Low-Cost, Highly-Integrated Silicon Carbide (SiC) Multichip Power Modules (MCPMs) for Efficient Electric Vehicle Chargers
- Transphorm (ADEPT) – High Performance GaN HEMT Modules for Agile Power Electronics
- Cambridge Electronics/MIT (ADEPT) – Advanced Technologies for integrated Power Electronics
- Solarbridge Technologies (Solar ADEPT) – Scalable Submodule Power Conversion Methods for Power Density, Efficiency, Performance, and Protection Leaps in Utility-scale Photovoltaics
- Monolith Semiconductors (SWITCHES) – Advanced Manufacturing and Performance Enhancements for Reduced-cost Silicon Carbide MOSFETs
- Soraa (OPEN 2009) – Ammonothermal Bulk GaN Crystal Growth

DEVELOPING POWERFUL AND EFFICIENT ELECTRIC POWER CONVERTERS

Updated: February 24, 2016

PROJECT TITLE: Low-Cost, Highly Integrated, Silicon Carbide Multi-Chip Power Modules for Plug-in Hybrid Electric Vehicles
PROGRAM: Agile Delivery of Electrical Power Technology (ADEPT)
AWARD: $3,914,527
PROJECT TEAM: Arkansas Power Electronics International (APEI) (Lead), Cree Power and RF (now Wolfspeed); Oak Ridge National Laboratory; Toyota Motor Engineering & Manufacturing North America; University of Arkansas
PROJECT TERM: September 2010 – March 2014
PRINCIPAL INVESTIGATOR (PI): Dr. Ty McNutt

TECHNICAL CHALLENGE

Thirty percent of U.S. electric power flows through power converters to support electric motors, HVAC, battery chargers, data centers and electric power generation and distribution. Unfortunately, incumbent power electronics technologies, which are based on silicon (Si) devices, are susceptible to breakdown under high voltage, limited to low switching frequencies, and perform poorly at high-temperatures. As a result, Si-based devices waste as much as 10% of the power that passes through them, which prevents Si-based systems from operating at improved efficiencies. One recent estimate predicted that within the next 20 years, 80% of the electricity used in the U.S. will flow through power electronics systems—which underlines the critical need to improve their efficiency, which would result in billions of dollars in energy savings.[11] Power electronics systems and devices based on new materials and improved circuit design techniques are the key to achieving substantially higher electrical power conversion efficiency and performance across the broad array of power electronics applications.

TECHNICAL OPPORTUNITY

Achieving higher energy efficiency and performance requires low-loss power semiconductor switches with significantly better performance than incumbent Si-based transistors and thyristors. Wide bandgap (WBG) semiconductor devices provide system designers with new opportunities to create systems with higher efficiency, higher temperature, and higher frequency than previously achievable. Substantial technical progress has been made on WBG-based power switches over the past decade creating the potential for new high-performance, high-efficiency power electronic systems from qualified, commercial devices.

Engineers used SiC MOSFETs to create a charger (black) six to seven times faster than the current on-board charger (silver) of a 2010 Toyota Prius Hybrid. The device can also charge the vehicle in one-third of the time required by the standard charger.

INNOVATION DEMONSTRATION

The APEI team (now the Wolfspeed team, a new team comprised of the former APEI team and Cree's Power & RF division) aimed to revolutionize WBG power electronics systems by developing a high-performance Silicon Carbide (SiC) based power module and associated gate driver that

[11] L.M. Tolbert, et al., "Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications: Assessing the Technical Needs for Utility Applications. " (Oak Ridge, TN: Oak Ridge National Laboratory, 2005).

would improve overall performance through the reduction of electrical parasitics, enabling higher frequency operation and higher power density. To accomplish this, the team incorporated an advanced SiC multichip power module (MCPM) power packaging concept with a tightly integrated, high temperature gate driver board. The development of the new module was based on coupling Wolfspeed's SiC transistor (MOSFET) design with packaging technology specifically optimized to maximize the performance of the SiC chip for low inductance, higher temperature capability, and a small gate loop through high-level gate driver integration.

The new module was integrated into a Toyota 2010 Prius Plug-In Hybrid Electric Vehicle Platform to demonstrate the performance of the module and Wolfspeed's SiC-based system design philosophy. The project team developed and demonstrated a 6.2 kW Plug-In Hybrid Electric Vehicle (PHEV) onboard battery charger that is more than ten times smaller and lighter than existing state-of-the-art 1 kW Si-based chargers. The SiC-based charger cut system losses nearly in half, increasing operational efficiency to greater than 96% - and greatly reduced the time needed to charge an electric vehicle (EV) battery.

PATHWAY TO ECONOMIC IMPACT

The module developed in this work is now represented in an active product line, the HT-4000 series of power modules and an associated evaluation gate driver board (http://www.apei.net).

Wolfspeed's demonstration of the plug-in vehicle charger technology was recognized with an R&D 100 award in 2014, distinguishing it as one of the top technological breakthrough products released in 2013. This recognition has resulted in follow on funding from the Department of Energy's Vehicle Technology Office (VTO) for the development of a traction drive for the Toyota Prius platform and for a traction inverter targeted at the Ford EV platform using Wolfspeed's existing high-performance module lines.

The SiC charger technology was part of the portfolio that contributed to APEI's acquisition by its project partner, Cree, in July of 2015. Cree's Power and RF business, now known as Wolfspeed, seeks to accelerate the market for high-performance, best-in-class SiC power modules.

LONG-TERM IMPACTS

The onboard vehicle battery charger demonstrated during this project has been widely discussed in industry since its introduction into the technical marketplace. This project demonstrated one of the first commercial-facing high power systems incorporating SiC MOSFETs, showing that SiC device technology enables higher efficiency systems and a potential for 10-fold increase in both gravimetric and volumetric power density. This project also demonstrated that the system-level savings achieved using SiC devices can be large enough to justify their widespread adoption, despite the present higher cost of the component SiC devices relative to the Si devices they can replace.

With greater than 30% of all electricity generated today processed by power electronics systems, reducing the energy losses in Si-based devices would significantly reduce U.S. energy use, and even more in the future. By developing more effective power conversion systems, that are used in applications from battery chargers and traction drives in electric vehicles to connecting photovoltaics and wind turbines to the electric grid, it is possible to drive down the costs associated with these clean energy applications, making them more marketable and viable for consumer and industry adoption. In particular, this project's demonstration that overall system costs can be reduced despite using more expensive components is extremely important for continuing the adoption of commercially available, more efficient, WBG semiconductor power devices.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the APEI/Wolfspeed team's project has generated three invention disclosures to ARPA-E and one U.S. Patent and Trademark Office (PTO) patent:

Patents

"Vertical power transistor with built-in gate buffer," (11/10/2015), Patent No 9184237, Washington, DC: U.S. Patent and Trademark Office.

The APEI/Wolfspeed team has also published the scientific underpinnings of this technology extensively in the open literature. A list of publications resulting from this project is provided below:

Publications

Cole, Z., Passmore, B., Whitaker, B., Barkley, A., McNutt, T., & Lostetter, A. (2013). A High Temperature, Fast Switching SiC Multi-chip Power Module (MCPM) for High Frequency (> 500 kHz) Power Conversion Applications. *High Temperature Electronics Network (HiTEN)* 2013, Oxford, UK, July 8 - 10, 2013.

Lamichhane, R., Ericsson, N., Frank, S., Britton, C., Marlino, L., Mantooth, A., Francis, M., Shepherd, P., Glover, M., Perez, S., Mcnutt, T., Whitaker, B., & Zach Cole, Z. (2014). A wide bandgap silicon carbide (SiC) gate driver for high-temperature and high-voltage applications. *2014 IEEE 26th International Symposium on Power Semiconductor Devices & IC's (ISPSD)*. 414-417.

Mudholkar, M., Ahmed, S., Ericson, M., Frank, S., Britton, C., & Mantooth, H. (2014). Datasheet Driven Silicon Carbide Power MOSFET Model. *IEEE Transactions on Power Electronics IEEE Trans. Power Electron.,* 2220-2228.

Nance, E., Frank, S., Britton, C., Marlino, L., Ryu, S., Grider, D., Mantooth, A., Francis, M., Lamichhane, R., Mudholkar, M., Shepherd, P., Glover, M., Valle-Mayorga, J., Mcnutt, T., Barkley, A., Whitaker, B., Cole, Z., Passmore, B., & Lostetter, A. (2014). A 4H silicon carbide gate buffer for integrated power systems. *Power Electronics, IEEE Transactions, Volume 29 (2):* 539-542.

Shepherd, P., et al. (2014). Integrated Protection Circuits for an NMOS Silicon Carbide Gate Driver IC. *IMAPS High Temperature Electronics Conference (HiTEC)* 2014, Albuquerque, NM, May 2014.

Whitaker, B., Barkley, A., Cole, Z., Passmore, B., Martin, D., Mcnutt, T., Lostetter, A., Seung Lee, J., Shiozaki, K. (2014). A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices. *IEEE Transactions on Power Electronics IEEE Trans. Power Electron.,* 2606-2617.

Whitaker, B., Barkley, A., Cole, Z., Passmore, B., Mcnutt, T., & Lostetter, A. (2013). A high-frequency, high-efficiency silicon carbide based phase-shifted full-bridge converter as a core component for a high-density on-board vehicle battery charging system. *2013 IEEE ECCE Asia Downunder.* 1233-1239.

Whitaker, B., Barkley, A., Cole, Z., Passmore, B., Mcnutt, T., & Lostetter, A. (2013). High-frequency AC-DC conversion with a silicon carbide power module to achieve high-efficiency and greatly improved power density. *2013 4th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG*). 1-5.

Valle-Mayorga, J., Rahman, A., & Mantooth, H. (2012). Back to the Future: An All-NMOS SiC Linear Voltage Regulator for High Temperature Applications. *2012 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS).* 1-4.

ULTRA FAST SWITCHING TECHNOLOGY FOR MOTOR DRIVES AND DC/AC INVERTERS

Updated: March 29, 2016

PROJECT TITLE: High Performance GaN HEMT Modules for Agile Power Electronics
PROGRAM: Agile Delivery of Electrical Power Technology (ADEPT)
AWARD: $2,950,000
PROJECT TEAM: Transphorm Inc. (Lead), UC Santa Barbara, Virginia Tech
PROJECT TERM: September 2010 – February 2013
PRINCIPAL INVESTIGATOR (PI): Dr. Primit Parikh

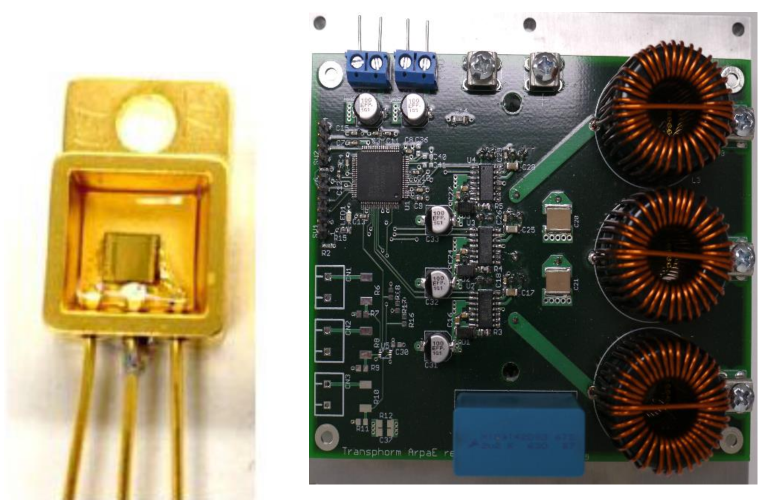
TECHNICAL CHALLENGE

Electricity generation from renewable sources and energy conservation through its efficient use are cornerstones of energy security and lower carbon dioxide emissions. Reducing energy loss during power conversion, such as when the DC output from a solar array has to be converted to AC for delivery to the power grid, is important for energy conservation. In addition, providing power that is optimized for driving electric motors, which presently account for nearly one half of U.S. industrial electricity consumption[12], and over one third of U.S. electricity use overall[13], can greatly improve their energy efficiency. The compact size of power conversion modules is also important—compactness allows retrofitting or embedding in machines.

TECHNICAL OPPORTUNITY

Achieving higher energy efficiency and performance requires low-loss power semiconductor switches. Wide bandgap (WBG) semiconductor devices can operate at far higher frequencies and with significantly lower losses than incumbent Si-based transistors and thyristors. WBG devices have demonstrated half the losses and ten times smaller size and weight compared with conventional power converters in a wide range of applications. In the years before this project began, substantial technical progress had been made on gallium nitride (GaN)-based high electron mobility transistors (HEMTs). Devices with the potential to operate at high-power density and significantly higher frequencies relative to silicon-based transistors had been demonstrated for radio frequency (RF) and microwave applications. However, most GaN power transistors at the time were fabricated on expensive silicon carbide (SiC) substrates and were normally-on devices (many safety critical applications require normally-off devices). The research community had started to show the feasibility of fabricating GaN devices on low cost Si substrates, and several approaches to achieving manufacturable normally-off devices had been proposed.

a. b.



a) Transphorm's GaN e-mode switch in metal package
b) Inverter on a card with low-pass filters giving true sinewaves

[12] https://www.eia.gov/todayinenergy/detail.cfm?id=18151

[13] Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems, Table 14 (IEA 2011)

Furthermore, a variety of new circuit concepts had been proposed that could take advantage of the higher (>1 MHz) switching frequencies potentially enabled by GaN devices.

INNOVATION DEMONSTRATION

Under ARPA-E support, Transphorm's goal was to advance the state-of-the-art in compact high efficiency power conversion by developing high performance GaN HEMT switches on low cost silicon substrates. Specifically the project team aimed to demonstrate high voltage (600V and 900V) GaN-on-silicon normally-off power switches that could be manufactured at competitive costs. To do so required Transphorm to overcome challenges of growing high quality GaN layers on Si substrates. This task was particularly challenging due to the mismatch of both crystal lattice structure and coefficients of thermal expansion mismatch between GaN and Si. The team addressed this issue by developing unique buffer layer structures between the GaN and Si, and developed normally-on devices. The team also demonstrated normally-off devices by developing a new gate region etch process combined with a modified process for growing a new stable gate dielectric.

Transphorm's GaN switches demonstrated significant advantages over silicon Si MOSFETs with lower gate charge and faster switching speeds in excess of 150 V/ns. This can be compared to current silicon technology with switching rates less than 50V/ns.

Under the ADEPT program's support, Transphorm packaged the ultra-fast GaN normally-on switches as cascodes in a 3-phase bridge and demonstrated a 3 kW motor drive operating at >100 kHz with <1.5% loss, with aspirations to expand the power level to >20 kW in the future. Transphorm's GaN-based system resulted in a six times size reduction over the silicon incumbent technology (a Si IGBT motor drive operating at 10-20 kHz with approx. <5% loss). The drive also incorporates on-board filters that enable generation of smooth 3-phase AC waveforms (sine waves) at 60 Hz. This drive with low distortion improves electric motor efficiency by reducing loss of energy in harmonics, reduces insulation failure by eliminating voltage spikes (which can occur in unfiltered drives), lessens mechanical vibration and bearing wear, and thereby extends motor life. These features enable speed control of cheaper non-inverter grade motors thus expanding the application space and overall energy savings. The development of this demo system facilitated Transphorm's efforts to partner with customers in their efforts to evaluate GaN devices and design GaN-based systems.

PATHWAY TO ECONOMIC IMPACT

In February 2013, Transphorm Inc. announced that its novel 600V GaN module has enabled the world's first GaN-based high power solar converter. Transphorm and its customer-partner Yaskawa Electric built the inverter, achieving several industry firsts including the first high power (4.5 kW) converter product in the world utilizing GaN technology, the first efficient PV power conditioner to operate at 50 kHz as well as a 40% reduction in inverter size with passive cooling and 98% efficiency. This was a significant demonstration of the size reduction and high efficiency that are form and function benefits attributed to the GaN module technology.

Transphorm's 600V GaN HEMT (TPH3006PS) was named 2013 Product of the Year by Electronic Products Magazine in the "Discrete Semiconductor" category.[14] Electronics Products Magazine highlighted the ability for Transphorm's product to enable compact, lower-cost power conversion systems in a wide range of applications including power supplies and adapters, PV Inverters for solar panels, motor drives, and chargers for electric vehicles.

ARPA-E's support of Transphorm's GaN HEMT technology development has led to significant interest and subsequent funding by many private investment groups. Following earlier rounds of funding from entities such as Kleiner Perkins Caufield and Byers, Google Ventures, Soros Quantum Strategic Partners, and Fujitsu, KKR led a $70 million round of investment in Transphorm in 2015.

[14] http://www.electronicproducts.com/Discrete_Semiconductors/Transistors_Diodes/First_qualified_GaN_HEMT_features_very_low_energy_losses.aspx

Transphorm has continued to expand its GaN transistor product portfolio since the conclusion of their ARPA-E project. Today, the company has more than 15 GaN/Si transistor products at various power levels on the market. The company offers a range of demo boards that can assist companies in their efforts to design power converters utilizing GaN devices.

LONG-TERM IMPACTS

Transphorm's work has significantly advanced the realization of energy efficiencies based on the use of GaN, and continues to do so through its ongoing investment in advanced GaN-based product and resource development. GaN/Si-based transistors offer a pathway to lower cost WBG devices in the 600-1200V device range. Combined with the potential for substantial system size reductions, it is expected that these devices can enable lower total power converter costs relative to systems based on Si transistors. The high frequency capability of GaN devices also enable new circuit topologies and/or system performance standards.

The continuing development of GaN/Si devices will take place in the competitive power electronics market. In 2014, GaN-based power devices accounted for about $10M market size with PV inverters, consumer and automotive applications. Compared to a total global power electronics market size of >$15B (2014), the GaN market portion is very small. However, the market is predicted to grow over the next 5 years as costs continue to come down making GaN devices more competitive with silicon and emerging SiC technologies. It has been predicted that by 2020, the total GaN power electronics market will reach approximately $0.55B with the automotive market making up almost 30% of the total.[15]

INTELLECTUAL PROPERTY

The Transphorm team's project has generated two patents issued by the U.S. Patent and Trademark Office (PTO).

Patents

"Electronic Components with Reactive Filters". (2014) *US Patent No. 8,786,327*. Washington, DC: U.S. Patent and Trademark Office.

"Method of forming electronic components with reactive filters" (2015) *US Patent No. 9,041,435*. Washington, DC: U.S. Patent and Trademark Office.

The Transphorm team has published the scientific underpinnings of this technology in the open literature and through conference presentations. A list of publications and presentations resulting from this project is provided below:

Publications

J.Honea, J. Kang, "High-Speed GaN Switches for Motor Drives", Power Electronics Europe, Vol. 3, pp. 38-41, 2012.

J.Honea, D. Kebort, Y. Wu, R. Welch, J. Kang, and K. Shirabe, "Using GaN Devices to Improve the Power Efficiency in a Motor-Inverter Drive System", Motor, Drive, and Automation Systems Conf. 2012, Orlando, FL, March 2012.

K. Shirabe, M. Swamy , J. K. Kang, M. Hisatsune, Y. Wu, D. Kebort, and J. Honea, "Advantages of high frequency PWM in AC motor drive applications," Proceedings of the 2012 IEEE Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, September 2012.

P. Parikh, Y. F. Wu, L. K. Shen, "Commercialization of High 600V GaN-on-Silicon Power Devices", Materials Science Forum, Vols. 778-780, pp. 1174-1179, October 2014.

R. Mitova, A. Dentella, M. X. Wang, R. Ghosh, U. Mhaskar, and D. Klikic, "Half Bridge Inverter with 600V GaN Power Switches" Proceedings of the PCIM Europe 2013 conference, Nuremberg, May 2013.

Y-F. Wu, D. Kebort, J. Guerrero, S. Yea, J. Honea, K. Shirabe and J. Kang, "High-Frequency, GaN Diode-Free Motor Drive Inverter with Pure Sine Wave Output" Power Transmission Engineering, Vol. 6 (5), pp. 40-43, 2012.

[15]Yole Développement report "GaN and SiC Devices for Power Electronics Applications" Jul.2015

POWERCHIP TO POWER THE WORLD

Updated: June 22, 2016

PROJECT TITLE: PowerChip: Advanced Technologies for Integrated Power Electronics
PROGRAM: Agile Delivery of Electric Power Technology (ADEPT)
AWARD: $4,414,003
PROJECT TEAM: *MIT (Lead)*, Dartmouth College, University of Pennsylvania, Georgia Tech
PROJECT TERM: September 1, 2010 – December 31, 2013
PRINCIPAL INVESTIGATOR (PI): Prof. David Perreault

TECHNICAL CHALLENGE

Conversion of electrical power from one form to another is achieved by power electronics. The application area is very broad as power electronics is the bottleneck in key systems such as solid-state lighting, solar and wind converters, motor drives (escalators, elevators, home appliances, HVAC), hybrid and electrical vehicles, and energy needs of rapidly growing data centers. Energy losses in the conversion processes themselves are significant, and even larger opportunities for energy savings exist in improved performance of the devices that are driven by the converted power. Low-loss, low-cost power conversion that can switch rapidly and maintain high-quality waveforms is needed to enable gains in energy efficiency across the application areas.

TECHNICAL OPPORTUNITY

The development of new wide bandgap semiconductor materials has opened new opportunities for higher energy efficiency and performance reliably in power electronics. Wide bandgap semiconductor devices can operate at far higher frequencies and with significantly lower losses than incumbent Si-based transistors and thyristors. However, the wide bandgap semiconductors devices are only part of a complete power converter, which also requires inductors and transformers. These are based on magnetic materials, where advances in nano-structured materials offer the potential for improved properties. Novel circuit architectures, topologies, and designs are required to exploit the progress made in semiconductor devices and magnetic components to achieve higher performance and greater system miniaturization. Successful development in this area draws on advances in semiconductor devices, magnetic components, and circuit aspects of the power system simultaneously.

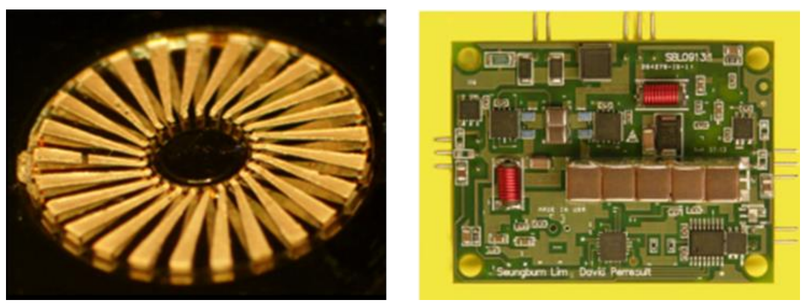


Figure 1. Microfabricated coreless inductor (left) and high frequency DC-to-DC converter (right)

INNOVATION DEMONSTRATION

Under ARPA-E support, the MIT project addressed all three areas needed to improve power conversion: switching devices, inductors, and circuit design. The goals of the project team were: to exploit the potential of GaN for high-power switching in practical, reliable devices; to create high-frequency inductors by developing new materials and designs, and to create overall circuit designs for power converters that optimally integrated the new components. As a final deliverable, the team aimed to integrate the innovations into a 10-50 W power converter with an input of 100 V, >93% efficiency, 5 MHz switching frequency, and power density of 300 W/in^3.

First, enhancement-mode gallium nitride (GaN) high electron mobility transistors (HEMTs) capable of withstanding 600 V were made. This advance is notable because GaN devices are typically depletion mode (normally-on), requiring more complex circuit design and affecting system reliability. MIT developed a new (tri-gate) design, reduced defect states with new etching and passivation approaches, controlling defects during GaN growth, and engineering the electric fields in the device to increase breakdown voltage. At the time of the project, there were a few commercial examples of GaN devices rated for 600 V, but those were based on depletion-mode devices. The MIT team was able to push the state-of-the-art 600 V operation in enhancement-mode.

Second, the team increased the power density of the converters by creating inductive elements capable of switching at 5 MHz, thereby shrinking their size. Georgia Tech used microelectromechanical (MEMS) fabrication processes to create solenoid and toroid inductors with and without magnetic cores, while drastically reducing the fabrication time and cost. Inductance values ranged from 60-800 nH and small signal quality factors were 8-45, which are comparable to commercial devices with a larger footprint.16 In parallel, the team developed magnetic core materials to achieve a higher efficiency and inductance with fewer inductor turns. These materials were then integrated with microfabricated toroids or hand-wound inductors made by Georgia Tech. Dartmouth created new core magnetic core materials from sputter-deposited Co-Zr-O nanocomposites; by applying a magnetic field during deposition, the team produced a material with local anistropy that allowed them to achieve an efficiency of 96% and quality factor of 50 over the 10-50 MHz range. UPenn developed nanocomposite magnetic core materials with high permeability but low dielectric loss. They key was creating nanoscaled particles with nearly identical sizes. When integrated into toroidal micro-inductors, they demonstrated an efficiency of 93% at 5 MHz and a 40 W load.

Another group at MIT analyzed and optimized the design of the full range of microfabricated cored and coreless inductors. They developed models to estimate the energy stored and power dissipated and built an equivalent circuit model to analyze the performance over a wide range of inductor designs and transistor sizes. The results were used to design the inductors used in the final LED driver deliverable for the project.

Finally, MIT developed new circuit topologies to take advantage of the enhancement-mode GaN HEMTs and the high frequency inductors. A two-stage architecture was created to accommodate frequencies of 3-30 MHz and a wide range of DC or AC input. The team demonstrated a DC-to-DC LED driver with an input of 100 V and output power of 41 W. The efficiency was 94% and the box power density was 406 W/in^3. The team also built an AC-to-DC converter with an efficiency of 93.3% and power factor of 0.89 at frequencies between 3-30 MHz, achieving an overall box power density of 50 W/in^3. Current LED drivers operate in a frequency range of 50-100 kHz, have a maximum efficiency of 85%, and power density <5 W/in^3.

PATHWAY TO ECONOMIC IMPACT

The project showed a proof of principle that a broad range of input voltages could be accomodated by one converter at high frequencies. The test circuits at MIT demonstrated higher efficiencies and power densities than larger, commercial circuits. In June 2016, an MIT spinout company named FINsix began shipping DART, a 65 W laptop charger that is 3 times smaller and lighter than convetional chargers. The circuit design concepts created during the ARPA-E project and the lessons learned directly informed the design of the DART charger. In January 2016, FINsix and Lenovo announced a partnership to make the smaller charger available for select ThinkPad models. Concurrently, the team is collaborating with major power electronics companies such as Texas Instruments to design converters in the range of tens to hundreds of Watts. LED drivers are a second initial market.

The novel GaN transistor technology developed during the project was the key IP to start the company Cambridge Electronics (http://www.gantechnology.com). This company, started by students whose research was originally funded by the ARPA-E project, licensed the IP from MIT and is currently offering state-of-the-art GaN devices for sale to selected partners. The company has received numerous awards, including the Massachusetts' MassVentures Start Award (Phase I and II) as well as the 2016 Compound Semiconductor Industry Award (http://www.csawards.net/).

LONG-TERM IMPACTS

The MIT project has proven the viability of shrinking power converters by moving to higher frequencies. Smaller form factors will accelerate deployment of LEDs and reduce the size of converters for widespread technologies such as

[16] See for instance: http://www.murata.com/en-us/products/inductor/chip/feature/rf, http://electronics.stackexchange.com/questions/190953/q-factor-in-inductors

laptops. The team also demonstrated efficiencies greater than 90%, compared to 85% today. If every new laptop shipped in the U.S. had this higher efficiency, it would save 46 gigawatt-hours of electricity per year. Furthermore, the team's research in the field of magnetic materials for inductors could revolutionize how power converters are designed and operated. Existing commercial materials with low magnetic permeability could be incorporated into these new circuit designs at frequencies such as 10 MHz, drastically increasing the power density from 5 W/in^3 to more than 300 W/in^3 while reducing electrical losses.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of June 2016, the MIT team's project has generated 9 invention disclosures to ARPA-E, 7 non-provisional U.S. Patent and Trademark Office (PTO) patent applications, and 2 U.S. patents issued by PTO.

Patents

"*Diode having trenches in a semiconductor region*," (3/22/2016) Patent No 9,293,538, Washington, DC: U.S. Patent and Trademark Office.

"*Semiconductor devices having a recessed electrode structure*," (5/26/2015) Patent No 9,041,003, Washington, DC: U.S. Patent and Trademark Office.

The MIT team has also published the scientific underpinnings of this technology extensively in the open literature. A list of publications is provided below:

Publications

Araghchini, M., Chen, J., Doan-Nguyen, V., Harburg, D. V., Jin, D., Kim, J., . . . Sullivan, C. R. (2013). A Technology Overview of the PowerChip Development Program. *IEEE Transactions on Power Electronics IEEE Trans. Power Electron., 28*(9), 4182-4201. doi:10.1109/tpel.2013.2237791

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CHANGING WHAT'S POSSIBLE

CAPTURING SOLAR ENERGY EFFICIENTLY

Updated: April 26, 2016

PROJECT TITLE: Scalable Submodule Power Conversion for Utility-Scale Photovoltaics	
PROGRAM: Solar Agile Delivery of Electrical Power Technology (Solar ADEPT)	
AWARD: $1,749,408	
PROJECT TEAM: SolarBridge Technologies (Lead); University of Illinois, Urbana Champaign	
PROJECT TERM: February 2012 to June 2015	
PRINCIPAL INVESTIGATOR (PI): Dr. Patrick Chapman	

TECHNICAL CHALLENGE

Photovoltaic (PV) solar systems convert the sun's energy into electricity, but only a small percentage of the sunlight reaching a PV system is converted into useful electricity. This is partly because the type of electricity (low voltage, direct current) that comes from a PV system must be converted to higher voltage and alternating current before it is transmitted to customers, and this process is inefficient in most PV systems today. The inefficiency arises because the individual panels in a PV system are linked together (in series), and their combined electrical output has historically been processed by one central converter. In this case, because there are variations in performance among the panels (either due to manufacturing, or as a result of shading, wear or damage), the weakest panel limits the energy production of the entire system. More effective conversion could increase yield of useful electricity from PV systems by several percent, however the cost of the improved electronics must be low (<$0.10/Watt) to keep renewable solar energy cost-competitive.

TECHNICAL OPPORTUNITY

The "central converter" topology has been the workhorse of the PV industry, as it provides a straightforward implementation for large-scale systems. However, a standard central inverter cannot provide the individual adaptations needed (power point tracking (PPT)) to operate each panel at the voltage and current where it is most efficient. This is because the central converter cannot distinguish, measure, or address the panels separately. Applying the concept of differential power processing (DPP), however, has the potential to address this problem. Electronic DPP circuitry optimizes the output energy from each panel separately – and then combines the outputs for delivery to a central DC-to-AC converter, as shown in Figure 1 on the right. A key aspect of DPP is that it uses smart signal processing and computational circuits to sense and process only the *mismatched* power—which is typically a small percentage of the total power produced by the PV panel array.

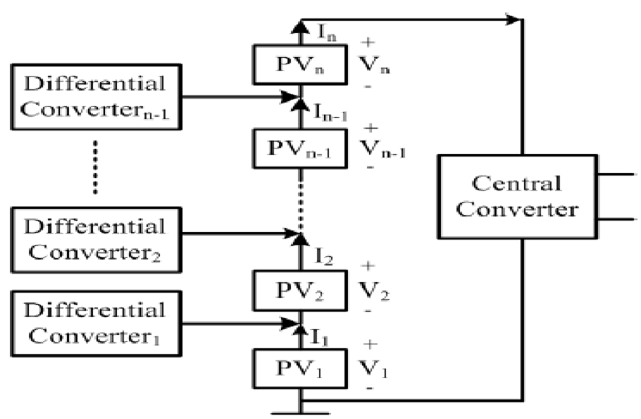

Figure 1. Basic Differential Power Processing Concept. At the module or sub-module level, the differential power processors – or differential converters – inject small amounts of electrical current at the nodes between each panel (or, in some cases, sub panels), shown as PV1 through PVn in the figure. The injected currents are set to correct for sensed imbalances in the currents generated across the PV elements due to shading or performance mismatches – thus enabling the entire array to operate nearer to its optimum energy conversion state

INNOVATION DEMONSTRATION

Although the technical aspects of DPP have been well-understood, the key challenge under ARPA-E support was to develop integrated DPP technology that will increase harvesting efficiency while contributing to a total power inverter cost less than $0.05/W. With this goal, SolarBridge, with its partner the University of Illinois at Urbana-

Champagne (UIUC), developed two distinct DPP architectures—one as a stand-alone unit and another as a micro-inverter-integrated unit. Both architectures demonstrated enhanced energy harvesting capabilities. For the standalone DPP unit, UIUC applied novel circuit miniaturization and low-power integrated circuit design techniques. The other DPP unit was developed jointly by SolarBridge and UIUC to be directly integrated within SolarBridge's off-the-shelf micro-inverter platform. Both units demonstrated greater than 95% converter efficiency (per the CEC standard) and greater than 99.4% power point tracking effectiveness[17] (the ratio of input power to theoretical maximum input power). By comparison, although a central converter can achieve as high as 98% efficiency, the uncorrected mismatch (even without shading) in panels leads to a harvesting reduction of 5-8% over the life of the system. This means that the best the central converter can be expected to do is 98% x 95% ≈ 93% efficiency—giving the micro-inverter a ~2% advantage.

In laboratory tests, the DPP integrated micro-inverter showed a 4% increase in energy harvesting with 1 sub-string of the PV module shaded, and 20% increase with 2 shaded—thereby validating predicted performance enhancement. Analysis of out-door field tests show that, on average (for a typical geographic distribution), SolarBridge's DPP-based solar power conversion system can be expected to yield approximately 1.5% more annual energy harvest than the conventional methods

While developing the standalone DPP circuitry, UIUC identified and addressed a new critical challenge in performing maximum power point tracking (MPPT). MPPT is the control algorithm that tracks the voltage of a PV cell in order to maximize the power output. The team developed a novel "distributed" MPPT algorithm for standalone DPP architectures and proved its robustness in a multi-sub-module load simulation experiment. Their new algorithm enables module "hot spot" (i.e., damaged or inoperative cells in the module that cause localized over-heating in the panel) detection via robust communication algorithms within distributed PV architectures.

In another illustration of the improvements possible with standalone DPP circuitry, UIUC performed an analysis to determine whether intentionally designing a PV array to have some degree of self-shading might be feasible. The core idea is that crowding more PV modules within a given footprint (such as on a rooftop) may provide a net increase in energy harvest even though more self-shading was present. With DPP mitigating the effects of shading, an optimum array pattern may be devised. In their analysis, UIUC showed that with 98% level of energy harvesting (i.e. 2% reduction due to self-shading) PV panels for a given output could be spaced closer allowing approximately 6.2% more modules to be placed in the same space.

PATHWAY TO ECONOMIC IMPACT

At the conclusion of the ARPA-E-sponsored program in 2015, SolarBridge (which was aquired by SunPower in 2015) indicated that the company will conduct economic analyses to determine whether the new micro-inverter integrated DPP circuitry developed under the SOLAR ADEPT program will provide a net postive impact on their highest-performance PV module products. Their preliminary assessment was that a slightly higher up-front premium would provide net benefits from improved yield over the lifetime of the system, but that customer acceptance would need to be determined.

The more versatile, but more expensive, standalone DPP circuitry has demonstrated significant potential performance benefits when combined with new MPPT algorithms. The detection of hot spots has the potential to increase the lifetime of PV systems from 22 years to 25 years, and the ability to adapt to space-limited sites, in which shading is a serious problem, may enable wider applications.

LONG-TERM IMPACTS

If the marginal costs of adding DPP to future PV systems can be further reduced, then the enhanced total conversion efficiency afforded by DPP may have a significant impact on future installations of PV systems. In particular, applications with variable cloud cover or constrained-space (e.g., urban commercial rooftops), where paying up-front premiums may

[17] Although "lab grade" tests, under ideal shade-free conditions, have yielded 99.8% power point tracking efficiency, the 99.4% achieved here with the DPP micro-inverter approach is a reasonable estimate of the highest tracking effectiveness level attainable in a practical system.

be feasible to maximize net harvested energy over the lifetime of the system, may be the earliest adopters of DPP technology. Critical to this will be developing an effective trade-off in upfront costs verses long-term harvesting payoff. Similarly, the enhanced MPPT algorithms and circuits, developed by UIUC may provide a path toward enhancing the lifetime of PV systems. The end-of-life pay-off versus up-front costs will require further techno-economic analyses to determine the potential impact. Finally, as panel costs continue to shrink relative to the balance-of-system costs, designing systems with some degree of intentional self-shading (to maximize overall long-term yield per cost) may become feasible due to the inclusion of DPP in power conversion elements.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of September 2015, the SolarBridge team's project has generated four invention disclosures to ARPA-E and two non-provisional patent applications. The team has also published the scientific underpinnings of this technology in the open literature. A list of publications is provided below:

Barth, C., Pilawa-Podgurski, R.C.N., "Dithering digital ripple correlation control for photovoltaic maximum power point tracking", IEEE Trans. Power Electronics, 2015.

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Kim, K.A., Shenoy, P.S., Krein, P.T., "Converter rating analysis for photovoltaic differential power processing systems," IEEE Trans. Power Electronics, vol. 30, no. 4, pp. 1987-1997, 2015.

Kim, K.A., Xu, C., Jin, L., Krein, P., "A dynamic photovoltaic model incorporating capacitive and reverse-bias characteristics," IEEE Journal of Photovoltaics, vol. 4, pp. 1334–1341, 2013.

Pilawa-Podgurski, R.C.N., Perreault, D.J., "Submodule Integrated Distributed Maximum Power Point Tracking for Solar Photovoltaic Applications," IEEE Transations on Power Electronics, vol. 28, no. 6, June 2013.

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Qin, S., Barth, C.B., Pilawa-Podgurski, R.C.N., "Enhancing microinverter energy capture with submodule differential power processing," IEEE Trans. Power Electronics, to appear, 2015.

Qin, S., Cady, S.T., Dominguez-Garcia, A.D., Pilawa-Podgurski, R.C.N., "A distributed approach to MPPT for PV submodule differential power processing," Energy Conversion Congress and Exposition (ECCE), 2013 IEEE , vol., no., pp.2778,2785, 15-19 Sept. 2013.

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A NEW MODEL FOR WIDE BANDGAP SEMICONDUCTOR MANUFACTURING IN THE U.S.

Updated: March 17, 2016

PROJECT TITLE: Advanced Manufacturing and Performance Enhancements for Reduced Cost Silicon Carbide MOSFETS (AMPERES)
PROGRAM: Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES)
AWARD: $3,225,000
PROJECT TEAM: Monolith Semiconductor (Lead), X-Fab Texas, Rensselaer Polytechnic Institute, United Technologies Research Center, University of Arkansas
PROJECT TERM: January 2014 – December 2016
PRINCIPAL INVESTIGATOR (PI): Dr. Kevin Matocha

TECHNICAL CHALLENGE

Power semiconductor devices are critical to America's energy infrastructure—all electronics, from laptops to electric motors, rely on them to control or convert electrical energy to operate properly. Despite their importance in our energy infrastructure, today's power semiconductor systems are based on silicon semiconductors which are energy inefficient, have a limited upper operating temperature, and the silicon-based (Si-based) power converters have a large form factor (due to the large magnetic components required at low switching operating frequency) making them bulky and heavy. Innovative new semiconductor materials, device architectures, and fabrication processes are needed to improve the performance and efficiency of existing electronic devices and to pave the way for next-generation power electronics. Emerging semiconductor materials remain significantly more expensive than the silicon devices they seek to displace, thus limiting their widespread adoption. This remains a significant engineering challenge.

TECHNICAL OPPORTUNITY

Achieving higher energy efficiency and performance requires low-loss power semiconductor switches with significantly better performance than incumbent Si-based transistors and thyristors. Wide bandgap (WBG) semiconductor devices provide designers with the capability to create systems with higher efficiency, higher temperature tolerance, and higher frequency than previously achievable. Substantial technical progress has been made on WBG-based power switches over the past decade creating opportunities to develop new high-performance, high-efficiency power electronic systems. In particular, Silicon Carbide (SiC) is an emerging power WBG semiconductor because its electrical, thermal, and mechanical properties allow it to surpass the performance of conventional silicon power technology. It is an excellent candidate for next-generation high-temperature, high-frequency switching devices for commercial applications including industrial motor control and DC to AC inverters to enable renewable energy adoption. Today, SiC devices are significantly more expensive than Si devices. However, new opportunities for substantial cost reductions have materialized in recent years as larger 6” substrates have become available and SiC device fabrication processes have become more mature.

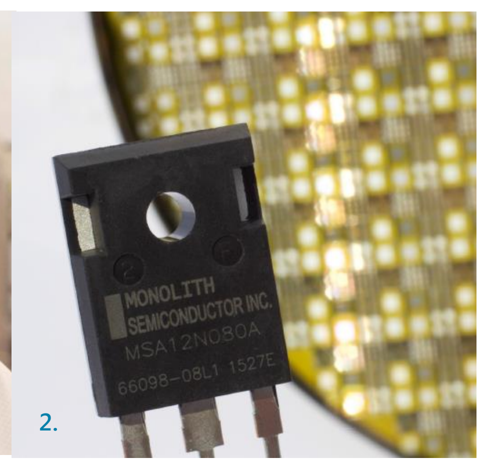

Figure 1. Processed Silicon Carbide Wafer at Foundry
Figure 2. Monolith Device with SiC Wafer in Background

INNOVATION DEMONSTRATION

Working within the ARPA-E SWITCHES program, Monolith Semiconductor's project goals are to develop 1) high performance SiC-based power diodes and transistors operating at 1200 V and 100 A, and 2) a high-volume, low-cost manufacturing process that is capable of delivering the devices at low cost (≤ $0.10/A). The Monolith team's approach is to design SiC devices and fabrication processes that are compatible with existing high-volume silicon manufacturing facilities to help drive down the cost of SiC devices.

To accomplish this, Monolith Semiconductor is partnering with X-Fab Texas, a high volume 150mm silicon semiconductor manufacturing foundry, to develop all of the process and manufacturing innovations required to enable SiC metal–oxide–semiconductor field-effect transistor (MOSFET) fabrication on 150mm SiC wafers in X-Fab's complementary metal-oxide semiconductor (CMOS) manufacturing facility. Specific challenges for SiC devices involve creating designs that are compatible with standard Si processing steps as much as possible, while optimizing the performance of the SiC power devices. An initial processing challenge was the optically transparent SiC wafers, which were difficult to handle on many of the existing Silicon fabrication processes and tools that rely on different methods for positioning and moving Silicon wafers. Monolith and X-Fab developed processing and tool updates to allow processing of transparent SiC wafers on the silicon production line.

Special consideration needs to be applied to the gate oxide process for SiC MOSFETs, as the formation is more difficult compared to Si and can easily result in degraded device performance. Monolith has developed state-of-the-art SiC MOSFET gate oxides, and through a partnership with the National Institute of Standards and Technology (NIST) has quantified the long-term reliability of these oxides operating at temperatures up to 300°C. The team has demonstrated design and fabrication success with SiC diodes and MOSFETs on the production line. Initial device yields on 150mm diameter SiC substrates using standard Si processing steps were low due to insufficient process margins for the SiC devices. Device design changes and processes improvements were implemented to improve the SiC process margins and increase the yield to commercially acceptable levels. The team has demonstrated high-power SiC diodes comparable in performance to the state-of-the-art. The Monolith team has also designed a prototype novel, high-performance 1200 Volt SiC power MOSFET with a specific on-resistance <3 mΩ-cm2 . The team is continuing to develop advanced device designs and processes to further reduce cost and improve performance. Their goal is to demonstrate 1,200 Volt SiC MOSFETs with currents >100A in a high frequency boost converter to quantify the performance advantages of their devices. The boost converter will enable a direct comparison to the current state-of-the-art to gauge performance and competitiveness of the value chain.

Working in an active Si foundry provides significant cost benefits. By using the existing silicon manufacturing infrastructure, Monolith can dramatically reduce the overhead costs to manufacture SiC devices, while maintaining high quality taking advantage of X-Fab's existing silicon process controls and quality systems. The equipment, labor, and utility costs, are spread over the large volume of wafers (silicon and SiC) processed at X-Fab. Monolith gains the cost advantage of high volume production even during initial low volume production of SiC devices. This approach is demonstrating the potential for significant cost savings over other competing SiC device manufacturing approaches, which use small or captured fabrication facilities.

PATHWAY TO ECONOMIC IMPACT

The combination of Monolith Semiconductor's SiC MOSFET design, low–cost process, use of 6" SiC wafers, and a silicon foundry manufacturing model is demonstrating promise to dramatically reduce the cost of SiC high voltage switches.

Monolith Semiconductor's innovative device and manufacturing model together with their demonstrated early device yields and high blocking voltages (>1200V) has attracted investment from the Army Research Laboratory, and in December 2015 they announced a strategic partnership with circuit protection device company Littelfuse Inc. of Chicago, IL. This relationship will accelerate development and help bring silicon carbide technology to the market, increasing customer reach as well as providing access to global channels through Littelfuse's deep sales and marketing expertise.

Monolith Semiconductor is also an active member of the DOE-supported National Network for Manufacturing Innovation (NNMI) PowerAmerica institute, which is led by NC State University, set up to advance the deployment of WBG semiconductor based power electronics in the U.S.

LONG-TERM IMPACTS

While SiC is already gaining traction in some energy-intensive applications, significant cost reductions, as being pursued by Monolith Semiconductor, will enable adoption of SiC devices in a variety of power electronics applications, including vehicles and motor drives. This will contribute to drive advances in power electronics and help facilitate greater adoption of electric vehicles, which in turn will help reduce U.S. oil imports. Moreover, efficient power electronics systems promise reduced electricity consumption, resulting in fewer harmful energy-related emissions. Lastly, the manufacturing model Monolith Semiconductor is demonstrating for SiC could trigger a breakthrough approach in the way companies accelerate the adoption of emerging technologies within the existing semiconductor value chain.

INTELLECTUAL PROPERTY

The Monolith team's project has generated two U.S. Patent and Trademark Office (PTO) patent applications.

LOWER COST GAN FOR LIGHTING AND ELECTRONICS EFFICIENCY

Updated: March 28, 2016

PROJECT TITLE: Ammonothermal Growth of GaN Substrates for LEDs and Power Electronics	
PROGRAM: OPEN 2009 and Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES)	
AWARD: $6,544,259	
PROJECT TEAM: Soraa	
PROJECT TERM: January 2011 – January 2016	
PRINCIPAL INVESTIGATOR (PI): Dr. Mark D'Evelyn	

TECHNICAL CHALLENGE

Light-emitting diodes (LEDs) and advanced power electronics devices can greatly improve energy efficiency across all U.S. energy sectors. LEDs are 5-10 times more efficient than incandescent bulbs, and advanced power electronic devices could reduce U.S. energy consumption by at least 1.5% annually by displacing lower-efficiency silicon devices. Gallium nitride (GaN) is a material that could enable both of these technologies. However, adoption into large-scale applications has been inhibited by high costs, which are due in part to the absence of inexpensive native substrates; GaN substrates are difficult and expensive to fabricate. But if highly efficient, low-cost LEDs fabricated on native substrates are deployed widely in both commercial and residential applications, the new native-substrate-based LED technologies could lead to savings of up to 350 terawatt-hours of electricity per year (an 8.5% reduction), roughly equivalent to the output of forty five 1,000-megawatt power plants.

TECHNICAL OPPORTUNITY

GaN substrates today are made by hydride vapor phase epitaxy (HVPE) on sapphire substrates. Although HVPE deposits material quickly, the number of wafers that can be packed into a reactor is limited. Also, the quality of materials currently made by HVPE is not sufficient for advanced power electronics applications. A key to low-cost and high-quality GaN substrates could be found in large ammonothermal reactors (Figure 1). Although these have a lower growth rate than HVPE reactors, they can load many wafers, and grow them thicker so that multiple GaN wafers could be sliced from one seed. If large-scale ammonothermal reactors (which have never been demonstrated commercially in the U.S.) could be proven with a crystal growth rate of 10 microns per hour, they could produce lower cost and higher quality GaN than is possible by HVPE.

INNOVATION DEMONSTRATION

The goals of the Soraa OPEN 2009 project included building a 6 inch diameter ammonothermal reactor, prove it could be operated safely, grow high quality GaN crystals at a rate of at least 10 microns per hour, and demonstrate growth of 2 inch bulk GaN crystals and fabrication of 2 inch GaN wafers (Figure 2). The ammonothermal GaN crystal growth method is adapted from the hydrothermal method used to grow quartz crystals, which are very inexpensive and represent the second-largest market for single crystals for electronic applications (after silicon). Soraa also received an award through the Strategies for Wide-Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES) program, to conceptually demonstrate they could scale a reactor

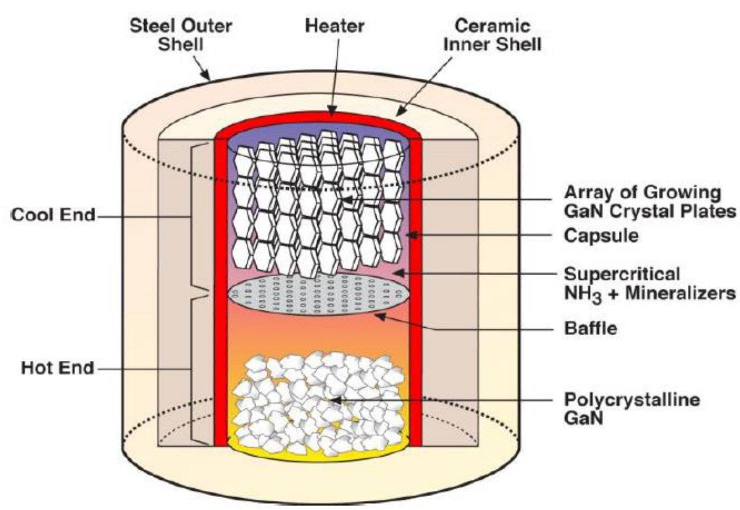

Figure 1. Ammonothermal reactor schematic

up to an even larger diameter, and fabricate wafers larger than 2 inches in diameter. Soraa successfully built a 6 inch reactor that is more than 350 times larger than earlier protoypes by overcoming challenges related to welding the capsule closed so that it does not leak, maintaining an even temperature distribution, and reinforcing the reactor to contain high pressure ammonia safely. The 6 inch ammonothermal reactor is capable of more than 600 degree Celsius operation and a pressure greater than 3,000 atmospheres; Soraa was able to grow GaN crystals at the target rate of 10 microns per hour and beyond. Soraa's reactor design and growth process eliminates leaking, improves temperature uniformity, optimizes internal loading of seeds and polycrystalline raw material, increases heater lifetime, and improves growth uniformity at all locations throughout the capsule.

Soraa has now operated the 6 inch reactor since 2011. Soraa has fabricated 2 inch wafers that meet their target specifications for LED crystal quality, dopant levels, dislocation density, miscut, and surface roughness. These wafers are sufficiently transparent to produce LEDs. Soraa has also shown that with additional processing steps, they have the ability to make wafers with a dislocation density less than 1×10^4 cm^{-2}, a breakthrough that will enable higher-peforming power electronics devices with a breakdown field greater than 3 MV/cm.

Figure 2. 2 inch GaN crystal and wafer fabricated by Soraa's process

PATHWAY TO ECONOMIC IMPACT

Soraa introduced its first commercial products, MR16 LED lamps, in 2012. These are made by depositing GaN on bulk GaN substrates. GaN-on-GaN growth results in fewer dislocations, allowing Soraa to drive their LEDs at a current density of 250 A/cm2 without a significant decrease in efficiency ("droop") compared to ~35 A/cm2 for GaN grown on sapphire[18]. This results in more light being produced from a smaller area.

Soraa's ammonothermal process is intended to produce substrates at a lower cost than is possible by current technology because it allows more and thicker samples in one run. Soraa is optimizing their growth process in the 6 inch reactor to create GaN crystals that can be sliced into wafers meeting LED specifications, which will then be used by Soraa to make LED lamps. Soraa will continue to improve their process to make lower dislocation density GaN crystals for power electronics applications. Ultimately, the goal is to build a commercial GaN growth facility.

LONG-TERM IMPACTS

Right now, GaN substrate vendors are focused on delivering substrates with a diameter of at least 2 inches, primarily for LED applications. Larger substrate sizes and higher substrate quality (lower dislocation densities) will be critically important for enabling higher power LEDs and power electronics devices based on GaN. Laser diodes are another potential application. But the wafer size will need to increase to 4 inch diameter and be sold for less than $1,500 to achieve widespread adoption, according to a 2013 report citing analysts at Yole, an authoritative source of industry projections in the power electronics domain.[19] Soraa has already shown they can build and safely operate 6-inch reactors that produce high quality ammonothermal GaN crystals. Semiconductor wafer sizes must continually increase in

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[18] "Soraa unveils GaN-on-GaN LEDs and MR16 lamps," LEDs Magazine, http://www.ledsmagazine.com/articles/2012/02/soraa-unveils-gan-on-gan-leds-and-mr16-lamps.html (2012)

[19] "LED applications to be key drivers for bulk GaN market," Semiconductor Today, http://www.semiconductor-today.com/features/PDF/SemiconductorToday_November2013-LED.pdf (2013)

order to drive down costs; Soraa's innovations will help to enable the continuous scaling of GaN wafers to 4 inches and beyond, which is necessary to achieve widespread penetration and improve U.S. energy efficiency.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of September 2015, the Soraa team's project has generated three invention disclosures to ARPA-E and three U.S. Patent and Trademark Office (PTO) patent applications. The team has also published the scientific underpinnings of this technology in the open literature. A list of publications is provided below:

W. Jiang, D. Ehrentraut, J. Cook, D. S. Kamber, R. T. Pakalapati, and M. P. D'Evelyn, "Transparent, conductive bulk GaN by high temperature ammonothermal growth," *Physica Status Solidi B* 252 (2015) 1069-1074.

W. Jiang, D. Ehrentraut, B.C. Downey, D.S. Kamber, R.T. Pakalapati, H. Yoo, and M.P. D'Evelyn, "Highly transparent ammonothermal bulk GaN substrates," *Journal of Crystal Growth* 403 (2014) 18-21.

W. Jiang, D. Ehrentraut, J. Cook, D. S. Kamber, R. T. Pakalapati, and M. P. D'Evelyn, "High quality, low cost ammmonothermal bulk GaN substrates," *Japanese Journal of Applied Physics* 52 (2013) 08JA01.

ENERGY EFFICIENCY AND CLEAN POWER – DIRECT AND ENABLING TECHNOLOGIES

Overview:

There is a compelling need for safe, clean, and cost-effective power generation technologies that will reduce carbon dioxide emissions and help position the U.S. as a global leader in renewable energy. ARPA-E has supported both innovative approaches to harvest renewable energy resources—solar, wind, geothermal—and key enabling technologies to make existing resources more cost-effective.

It is widely accepted that improving the efficiency of devices that use energy is the easiest pathway to reducing energy usage and carbon dioxide emissions. The key is to develop new, energy-efficient devices with comparable performance and cost to the devices they will displace. ARPA-E has supported a broad range of innovative technologies to improve energy efficiency, either directly, such as through the development of new air conditioning systems, or indirectly through projects that explore key enabling technologies that could be incorporated into a variety of energy systems to improve efficiency.

Many of the projects in efficiency and renewable energy resulted from the OPEN solicitations that provide the opportunity to develop technologies in areas not covered by existing or planned ARPA-E focused technology programs. These projects also complement the ongoing efforts of the Energy Efficiency and Renewable Energy Office in DOE by accelerating truly "out-of-the-box" concepts not currently on technology roadmaps.

The examples below represent a good sampling of the diversity and creativity of these projects:

- Makani (OPEN 2009) – Airborne Wind Turbine
- 1366 (OPEN 2009) – Direct Wafer: Enabling Terawatt Photovoltaics
- Foro (OPEN 2009) – Low-Contact Drilling Technology to Enable Economical EGS Wells
- Brookhaven/AMSC + U. Houston/SuperPower (REACT) – Superconducting Wires for Direct-Drive Wind Generators
- Stanford Radiative Cooling (OPEN 2012) – Photonic Structures for High-Efficiency Daytime Radiative Cooling
- Harvard SLIPS (OPEN 2012) – Novel Slippery Coatings for Extreme Energy-Savings
- UHV Technologies (METALS) – Low-Cost High-Throughput In-Line XRF Scrap Metal Sorter
- Phononic Devices (OPEN 2009) – Advanced Semiconductor Materials for High Efficiency Thermoelectric Devices
- Infinia Technology Corporation (ITC) – Stirling Air Conditioner (StAC) for Clean Compact Cooling

LAUNCHING ENERGY KITES

Updated: February 24, 2016

PROJECT TITLE: Airborne Wind Turbine (Energy Kite)	
PROGRAM: OPEN 2009	
AWARD: $6,000,000	
PROJECT TEAM: Makani Power	
PROJECT TERM: September 2010 – May 2013	
PRINCIPAL INVESTIGATOR (PI): Andrea Dunlap	

TECHNICAL CHALLENGE

There is a need for safe, clean, and cost-effective power generation technologies that will reduce carbon dioxide (CO_2) emissions and help position the U.S. as a leader in the global renewable energy industry. Currently, wind power provides 4.9% of U.S. end-use electricity demand in an average year.[20] However, expansion will be increasingly hampered by a scarcity of high-quality wind resources, which today limits generation to about 15% of U.S. land area, resulting in a limited resource and transmission grid congestion due to the physical distance of the existing resources to demand centers.

TECHNICAL OPPORTUNITY

Incremental advances in wind turbine technology will continue to be made by making turbines slightly larger and reducing traditional methods of supply chain costs. Transformative impacts are possible by completely reimagining wind power based on an airborne platform. The key insight is that the outermost 25% of a turbine blade delivers over 50% of the power. If the trajectory of an airborne generator can be made to follow the path of a conventional blade's tip, then this power can be harvested without building the non-productive infrastructure of a wind tower.

INNOVATION DEMONSTRATION

Makani Power set out to develop an Airborne Wind Turbine that accesses a stronger, more consistent wind at altitudes of between 500-1,000 feet. At these altitudes, up to 85% of the country can offer viable wind resources compared to only 15% accessible with current technology.

Makani's wind turbines resemble small airplanes. Rotors on each blade help propel the craft into the flight pattern, and double as turbines once airborne with motor generators connected to the rotors. The air vehicle is tethered to the ground with a cable that delivers power to the vehicle during launch, and then conducts the power generated by the turbines back to the grid-connected ground station.

Figure 1. Makani's 20 KW (average output when flying under optimal conditions) working prototype

The technical challenges the team faced at the start of the project were primarily in the complexity of automated controls and the tether system reliability. With ARPA-E's support, the Makani team developed solutions to these issues and demonstrated standalone lift off, hovering and touch down of a 26 foot wingspan vehicle, along with delivery of 7 kW of power down the tether.

[20] http://energy.gov/eere/wind/downloads/2014-wind-technologies-market-report

PATHWAY TO ECONOMIC IMPACT

Makani Power was acquired by X, formerly known as Google[X] in May 2013, toward the end of the ARPA-E award. The acquisition came just a week after the company completed its first fully-functional flight of its Wing 7 prototype.

X/Makani reports that it is making the transition to a commercial product: The team is increasing the power generation capacity of its Airborne Wind Turbine by 30 times and moving from the original hand-made prototype to mass production. The company's commercial product will be based on a 600 kW unit designed to deliver cost-competitive power. The team has worked through significant additional materials issues to design a tether with the goal of surviving the repeated stresses and cycles of operation. The company has also advanced its power systems for improved performance and reduced weight.

The X/Makani team is now testing its 600 kW model, moving from hover flights to test flights. From there the team will advance to cross-wind flights with power generation. The team is targeting operation between 400 and 1,100 feet. The anticipated operation would be in utility-scale wind farms with multiple units, and tighter positioning than ground-based turbines is expected due to lower wake effect.

LONG-TERM IMPACTS

Successful deployment and expansion of low-cost airborne wind power would create an entirely different technology for use of this renewable power source. By reducing geographic use restrictions, airborne wind farms will allow siting of wind generation in locations closer to population centers and where the existing transmission and distribution lines can be used effectively.

Additionally, the Makani wing may be economically efficient for use farther offshore than traditional wind turbines, providing an opportunity to tap an additional large wind resource.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the Makani project funded by ARPA-E resulted in two invention disclosures, two U.S. Patent and Trademark Office (PTO) patent applications, and two U.S. PTO issued patents:

Motor Pylons for a Kite and Airborne Power Generation System. US Patent 8955795. (2015) Washington, DC: U.S. Patent and Trademark Office.

Kite Ground Station and System. *US Patent 8888049.* (2014) Washington, DC: U.S. Patent and Trademark Office.

DIRECT MANUFACTURING OF SILICON WAFERS REDUCES COST AND IMPROVES PERFORMANCE

Updated: June 28, 2016

PROJECT TITLE: Direct Wafer: Enabling Terawatt Photovoltaics	
PROGRAM: OPEN 2009	
AWARD: $4,000,000	
PROJECT TEAM: 1366 Technologies	
PROJECT TERM: March 2010 – June 2012	

TECHNICAL CHALLENGE

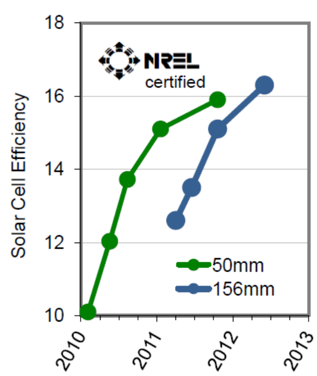
Crystalline silicon wafers contribute 40% to the total cost of a solar cell module, making the wafer the largest single cost contributor to photovoltaic installed costs ($4/W in 2009). While much effort is focused towards increasing the efficiency of solar cells using new materials (i.e. CIGS, CdTe, and organic photovoltaics), little attention has been paid to reducing the cost of the silicon wafer itself. As silicon remains the only stable, earth-abundant material demonstrated to be capable of obtaining low-cost, high efficiency, and commercial viability, cost reduction of the silicon wafer is crucial to further improve near-term commercial competitiveness of solar energy.

TECHNICAL OPPORTUNITY

Eliminating the most expensive and wasteful processes in silicon wafer manufacturing, casting and sawing, provides a strong potential to dramatically reduce the cost of manufacturing and increase silicon utilization. Traditional manufacturing requires sawing wafers from grown silicon ingots, which wastes approximately 50% of input silicon. Significant post-processing is also required to reduce impurities induced by sawing and achieve required wafer strength. Adoption of new, transformational manufacturing methods would impact the full silicon supply chain by reducing costs and enhancing production rates of silicon wafers, utimately enabling high penetration of low-cost solar cells, manufactured in the U.S.

INNOVATION DEMONSTRATION

The molten silicon Direct Wafer™ process developed by 1366 Technologies inherently reduces the cost and improves the strength and performance of the silicon wafer. The 1366 process of attaching molten silicon to a reusable substrate, solidying a thin sheet, and cleanly releasing a wafer eliminates the need for the sawing process, allows for controllable substrate formation, and increases the useable amount of silicon.



NREL Certification Date	Area cm^2	Voc mV	Jsc mA/cm^2	FF %	Eff
Feb. 5, 2010	4	559	23.8	76.0	**10.1%**
April 19, 2010	10	582	27.4	75.5	**12.0%**
July 13, 2010	20	589	30.7	75.9	**13.7%**
Jan. 18, 2011	20	599	32.9	76.5	**15.1%**
Oct. 25, 2011	19	605	34.2	77.0	**15.9%**
Oct. 31, 2011	**195**	600	33.6	74.0	**15.1%**
May 23, 2012	**223**	612	34.3	77.4	**16.3%**

Figure 1. Solar module efficiencies continued improvement during the ARPA-E project period. The graphical representation (left) summarizes improvements and technical details are provided in the table (right)

At the start of the project, 1366 Technologies had demonstrated proof-of-concept manufacturing of 50mm silicon wafers with 10% solar cell efficiencies using a direct molten-silicon process. Initial demonstrations were supported by a DOE Pre-Incubator Award, based on processes initially validated with tin. ARPA-E funding was provided to achieve industry-standard 156 mm solar cells, on par with multicrystalline silicon wafers. The specific goals were to 1) manufacture 156 mm Direct Wafer™ with average thickness 240 μm (+/- 20 μm), total thickness variation (TTV) <80 μm, and bow <100 μm; 2) demonstrate 16% efficient solar cell; and 3) achieve critical fracture stress equivalent or better than sawn wafer strength of 260 MPa.

Accomplishing the challenging metrics negotiated by ARPA-E required numerous innovations in manufacturing conditions and development of custom analytical techniques by 1366 Technologies.

The 1366 team first designed and built a customized furnace (named "Gen1"), enabling production and testing of industry standard 156 mm wafers. Meticulous control of Gen1 temperature conditions and resultant heat transfer and solidification rate resulted in enhancement of cell performance characteristics, leading to efficiency increases summarized in Figure 1. The final Gen1 furnace was theoretically capable of 5 MW wafer throughput with increased optimization of the manufacturing process.

Increasing wafer grain size from 0.8 mm to >1 mm was achieved by optimizing the reusable substrate for appropriate thermal conductivity and modifying thermal conditions of the furnace. A custom-built Laser Beam Induced Current system was used to validate grain size and differentiate grain boundary effects and intra-grain lifetimes. Thickness uniformity was similarly improved from 170 μm (+/- 25 μm) to 204 μm (+/- 48 μm) through modification of thermal conditions in the furnace.

The 260 MPa wafer strength is inherent to the Direct Wafer™ process. Fabrication from direct molten-silicon eliminates chemical and physical manipulation required to remove impurities and structural defects introduced in ribbon sawing, which weaken the wafer. Instead, low impurity wafers (<10 ppbw) are made by prepurifying molten silicon and condensing the wafers directly out of the melt.

PATHWAY TO ECONOMIC IMPACT

The demonstrated benefits of the Direct Wafer™ process led to over $70 million of follow-on funding from strategic and financial investors, including GE and Hanwha Q CELLS Co, Ltd., the world's largest solar cell manufacturer. Financing and technical accomplishments have gained coverage in The Wall Street Journal, The New York Times, and Forbes.

After the completion of the project in June 2012, 1366 Technologies leveraged external partnerships in downstream optimization of the full solar module and wafer production rate and steadily increased the efficiency of its solar cells. In August 2015, 1366 Technologies Direct Wafer™ wafers reported 19.1% full module efficiency using Hanwha's proprietary Q.ANTUM passive emitter rear contact process.

Manufacturing capacity greatly increased from the initial output of the Gen1 furnace. In 2013, a $6 million, 25 MW/yr capacity demonstration plant was built, enabled by Round B funding acquired during the ARPA-E award period. In 2015, 1366 Technologies met its initial 5 MW/yr throughput rate target, followed by installation of three 5 MW/yr capacity furnaces. Most recently, 1366 Technologies announced a 250 MW commercial Direct Wafer™ factory in New York State, scheduled to be online in 2017. The completed plant will provide Hanwha with 700 MW of wafers over a 5-year period. Financing will come, in-part, from a $150 million DOE loan guarantee, awarded in 2011. An additional $10 million commitment by Hanwha Investment Corporation to support plant construction was announced May 2016.

Efficiency and throughput enhancements led to utilization of wafers from the Direct Wafer™ process in a 20-module field test (completed February 2015) and a planned 1 MW solar installation in Japan under partnership with IHI Plant Construction Co.

LONG-TERM IMPACTS

Since 1366 Technologies award under the ARPA-E OPEN 2009program, the cost of silicon solar panels fell approximately $0.50/W per year between 2009 and 2013. Thus, the challenge of reducing silicon wafer cost is increased relative to the start of the program. In spite of the variable market, the 1366 Technologies high-throughput wafer manufacturing process is now capable of providing industry-standard 156mm drop-in silicon wafers directly from molten silicon at 20% cost reduction.

The continued support and integration of the 1366 Technologies process by the private sector, including Hanwha Q CELLS, Ltd. and IHI signifies strong potential for commercial success and cost-savings in solar module manufacturing.

The realization of the Direct Wafer™ process enables U.S. manufacturing of solar panels with greatly increasing production capacity.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of April 2016, the 1366 Technologies team's project has generated 4 U.S. Patent and Trademark Office (PTO) patents.

"Methods for efficiently making semiconductor bodies for making solar cells and the like", US Patent 8,293,009 granted October 23, 2012. Washington, DC: U.S. Patent and Trademark Office.

"Selected methods for efficiently making semiconductor bodies for making solar cells and the like", US Patent 8,696,810 granted April 18, 2014. Washington, DC: U.S. Patent and Trademark Office.

"Recrystallization of semiconductor wafers in a thin film capsule and related processes", US Patent 8,633,483 granted January 21, 2014. Washington, DC: U.S. Patent and Trademark Office.

"Porous lift-off layer for selected removal of deposited films", US Patent 8,669,187 granted March 11, 2014. Washington, DC: U.S. Patent and Trademark Office.

INNOVATIVE DRILLING TECHNOLOGY

Updated: May 17, 2016

PROJECT TITLE: Low-Contact Drilling Technology to Enable Economical Enhanced Geothermal System (EGS) Wells
PROGRAM: OPEN 2009
AWARD: $9,141,030
PROJECT TEAM: Foro Energy (Lead)
PROJECT TERM: January 2010 to September 2013
PRINCIPAL INVESTIGATOR (PI): Dr. Joel Moxley

TECHNICAL CHALLENGE

Vast geothermal reservoirs remain unexploited in the world due to their location in or beneath ultra-hard rock. When present, these layers of ultra-hard rock must be penetrated at depths of up to several kilometers. Current technology for drilling at this depth and hardness uses a roller cone or polycrystalline diamond compact (PDC) drill bit. Mechanical cutters are used to cut the rock, and the mechanically-fractured cuttings are removed to the surface using a flow of drilling "mud" – a water- or petroleum-based cocktail to transport the cuttings and manage formation pressure. These drilling operations cost in the millions of dollars to conduct, especially when the drill bits must be replaced often prematurely after operation in hard or abrasive rock. Additionally, drilling can take up to an hour to drill through just a few feet of rock with the typical need to drill through 100-500 or more feet of hard rock at well depths of up to 15,000 feet.

TECHNICAL OPPORTUNITY

According to a U.S. Geological Survey (USGS) report, there is enough geothermal energy resource in the U.S. to provide 517,800 megawatts of baseload geothermal electrical power[21]. However, much of this geothermal resource lies in or beneath very hard, low permeable rock (sometimes greater than 30 kpsi unconstrained compressive strength). Currently, there are no drilling technologies that can economically exploit this hard rock resource. Laser technologies that could offer faster and more efficient drilling options have been contemplated for some time. Until recently, laser drilling was i) incapable of penetrating beyond low lengths of rock; ii) unable to be delivered downhole because of laser conductance issues from surface levels down to the bottom hole assembly; and iii) not portable given large sizes and the precision alignment procedure of the laser. Recent advances in laser power transmission through fiber optic cables show great promise in delivering the required power at long distances down deep boreholes. This is a result of both the availability of cheaper and more powerful lasers as well as drastic cost reduction in fiber optic costs over the past 15 years, down from $1,000/W to less than $50/W. By combining powerful new laser and transmission technologies with conventional drill bits, an opportunity opened to exploit new geothermal resources.

Figure 1. Foro's Hybrid Laser-Mechanical Drill

[21]Williams, Colin F., Reed, Marshall J., Mariner, Robert H., DeAngelo, Jacob, Galanis, S. Peter, Jr., 2008, Assessment of moderate- and high-temperature geothermal resources of the United States: U.S. Geological Survey Fact Sheet 2008-3082, 4 p.

INNOVATION DEMONSTRATION

The overall goal of the Foro Energy team was to develop a world-first hybrid laser-mechanical drill assembly technology (Figure 1)[22]. The approach was to combine a rotating drill bit with a new laser transmission system to project laser radiation onto the rock surface while rotating. This kind of rapid heating fractures the rock, allowing a drill bit to remove rock cuttings from the rock surface, which exposes the next rock layer to be fractured by the laser.

To address the challenges, the engineers at Foro made significant advances in laser transmission technology. This included hardened optics, low-loss rotating optical connectors and fiber optics for the harsh downhole environment. The Foro team used its world-first technique to suppress Stimulated Brillouin Scattering (SBS)[23]. If unchecked, SBS will attenuate nearly all transmitted power at the frequencies and intensities being employed with this system. The dispersed power could easily destroy the fiber optic as well as the laser itself.

One of the key innovations of the Foro team was a high-power optical connector to couple the armored fiber optic cable transmitting power from uphole to the downhole beam shaping optics just above the drilling surface (Figure 2) that provides a uniform energy over the borehole surface. The connector successfully delivered 20 kW laser power to the downhole tool in the borehole at high ambient temperatures and in a high-shock environment, following aggressive testing of up to 24 hours at 400ºF and vibrational forces of 200 g's.

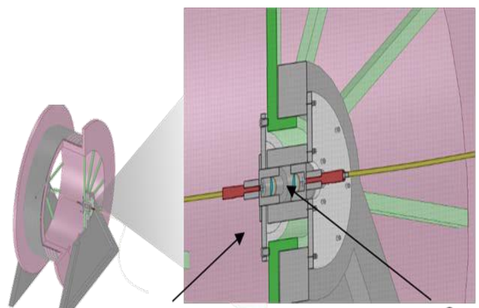


Figure 2. On the left, hardware image of the downhole laser connector, 0.75 inches in diameter and 8 inches long; on the right, illustration of the Optical Slip Ring (OSR), which allows the spooled fiber to be coupled with the rotating fiber optic, carrying power down the hole

One of the other notable innovations of the team was coupling the laser-power from the fiber optic cable as it unwinds from a storage spool to the fiber optic cable in the drill string, which is rotating. This was achieved using a novel Optical Slip Ring (OSR) (Figure 2) that optically couples the external fiber across a rotary joint to the optical fiber that carries the laser beam downhole. Precision rotary design enables over 20 kW of laser energy to be coupled from a laser input to the rotating Fiber Optic Cable, with rotational speeds up to 5 rpm. The combined advances in drill bit and laser technologies support accessing next-generation energy resources in a more timely and cost-effective manner.

Foro demonstrated the successful delivery of laser power through kilometers of hardened fiber optic cable to their experimental borehead assembly, with increased drill rates over state-of-the-art drills (10 ft/hr versus <3 ft/hr, respectively, in extremely hard rocks). Foro also demonstrated the utility of its hybrid laser—"drag-bit" technology—

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[22] "High Power Lasers - Long Distances" video. Produced by ARPA-E, accessible at youtube.com: https://www.youtube.com/watch?v=u5PX5u0qsqA

[23] SBS is a nonlinear scattering phenomenon that is driven by a positive feedback mechanism induced by the interaction of laser light with the fiber optic cable. Specifically, intermolecular forces act as a grating for transmitted light and a scattering event results in a wavelength-shifted light signal that deposits heat into the fiber.

normally only used for soft rock structures (100s of psi versus 100s kpsi for ordinary drilling), potentially increasing borehole assembly lifetime to drill up 300-500 feet of drilling.

During its ARPA-E project, Foro Energy demonstrated a world-first ability at surface to drill hard rock at 10 ft/hr over multiple hours of operation on test bedrock, as well as project 20kW laser energy for 12,000 feet distance in a rig-hardened fiber optic cable. While actual downhole tests were not carried out at this stage, the ARPA-E project opened the door to applications in drilling geothermal wells, and a novel technique for safe oil and gas well completion.

The combined advances in the hybrid laser and mechanical drilling technologies could support accessing next-generation energy resources in a more timely and cost-effective manner.

PATHWAY TO ECONOMIC IMPACT

During the performance period with ARPA-E and subsequently, Foro Energy has received investments from a number of investors, including but not limited to North Bridge Venture Partners, Presidio Capital, Formation 8, Chevron Technology Ventures, Energy Technology Ventures, and ConocoPhillips. The DOE Geothermal Office also recently funded a project for $3.5 million with the company to further develop its technology for geothermal borehole applications. The Foro team is also collaborating with Sandia National Labs in a separate Geothermal Office-funded project to validate and establish proof of concept for low weight on bit (WOB) drilling technology to be utilized in microhole (i.e., inches in diameter) drilling. Microdrilling methods aim to substantially lower geothermal well evaluation and monitoring costs.

Foro Energy has also moved its focus from research to development in collaboration with the company's target customer base for additional applications beyond drilling. In addition to their original research facility in Denver, Foro's now has offices in Houston, TX, Bakersfield, CA and a test well in Galveston, TX. As a first market, the team currently aims for its first product to be utilized in the closure and decommissioning of oil and gas wells, initial sales forecasted in 2016.

LONG-TERM IMPACTS

Foro Energy's technology could be a key enabler of economic access to megawatts of baseload geothermal electrical power. According to Foro's estimates, laser drilling could drop the cost of geothermal plants by up to 29% overall, since most of the cost of these plants is in drilling the wells themselves. In addition, Foro's technology could provide the world with a more efficient method of sealing oil and gas wells while at the same time preventing potential envioronmetal damage.

INTELLECTUAL PROPERTY

As of May 2016, this project has reported 41 invention disclosures to ARPA-E, 26 non-provisional U.S. Patent and Trademark Office (PTO) patent applications, and 18 U.S. PTO issued patents.

Patents

"Apparatus For Advancing A Wellbore Using High Power Laser Energy," (9/2/2014), Patent No 8,820,434, Washington, DC: U.S. Patent and Trademark Office.

"Control System For High Power Laser Drilling Workover And Completion Unit," (7/7/2015), Patent No 9,027,668, Washington, DC: U.S. Patent and Trademark Office.

"Electric Motor For Laser-Mechanical Drilling," (7/7/2015), Patent No 9,074,422, Washington, DC: U.S. Patent and Trademark Office.

"High Power Downhole Laser Cutting Tools And Systems," (1/20/2015), Patent No 8,936,108, Washington, DC: U.S. Patent and Trademark Office.

"High Power Laser Perforating Tools And Systems," (4/22/2014), Patent No 8,701,794, Washington, DC: U.S. Patent and Trademark Office.

"High Power Laser Workover And Completion Tools And Systems," (10/28/2014), Patent No 8,869,914, Washington, DC: U.S. Patent and Trademark Office.

"Laser Bottom Hole Assembly," (1/14/2014), Patent No 8,627,901, Washington, DC: U.S. Patent and Trademark Office.

"Long distance high power optical laser fiber break detection and continuity monitoring systems and method," (2/23/2016), Patent No 9,267,330, Washington, DC: U.S. Patent and Trademark Office.

"Method And Apparatus For Delivering High Power Laser Energy Over Long Distances," (8/20/2013), Patent No 8,511,401, Washington, DC: U.S. Patent and Trademark Office.

"Method And Apparatus For Delivering High Power Laser Energy Over Long Distances," (4/7/2015), Patent No 8,997,894, Washington, DC: U.S. Patent and Trademark Office.

"Methods And Apparatus For Delivering High Power Laser Energy To A Surface," (4/23/2013), Patent No 8,424,617, Washington, DC: U.S. Patent and Trademark Office.

"Methods And Apparatus For Removal And Control Of Material In Laser Drilling Of A Borehole," (1/28/2014), Patent No 8,636,085, Washington, DC: U.S. Patent and Trademark Office.

"Method And System For Advancement Of A Borehole Using A High Power Laser," (9/9/2014), Patent No 8,826,973, Washington, DC: U.S. Patent and Trademark Office.

"Method For Enhancing The Efficiency Of Creating A Borehole Using High Power Laser Systems," (6/24/2014), Patent No 8,757,292, Washington, DC: U.S. Patent and Trademark Office.

"Optical Fiber Configurations For Transmission Of Laser Energy Over Great Distances," (11/4/2014), Patent No 8,879,876, Washington, DC: U.S. Patent and Trademark Office.

"Optical Fiber Configurations For Transmission Of Laser Energy Over Great Distances," (10/29/2013), Patent No 8,571,368, Washington, DC: U.S. Patent and Trademark Office.

"Systems And Conveyance Structures For High Power Long Distance Laser Transmission," (3/4/2014), Patent No 8,662,160, Washington, DC: U.S. Patent and Trademark Office.

"Total Internal Reflection Laser Tools And Methods," (1/26/2016), Patent No. 9,242,309, Washington, DC: U.S. Patent and Trademark Office.

The Foro Energy team has also published the scientific underpinnings of this technology in the open literature. A list of publications resulting from this project is provided below:

Publications

Zediker, M. S.,Faircloth, B. O., Grubb, D. L., Kolachalam, S K., Schroit, S. N., Rinzler, C. C., Gray, W. C., Fraze, J., Norton, R., &Moxley, J. F. (2012). "High Power Fiber Laser Technology Developed for use in High G, Remote Environments." *Directed Energy Professional Society*. 12- SSDLTR-024, 2012.

Zediker, M. S., Faircloth, B. O., &Moxley, J. F. (2012). "High-power lasers in the energy industry." *Industrial Laser Solutions*, May 2012.

Zediker, M. S., "High power lasers for rock drilling." *Swiss Photonics: Photonics for Deep Geothermal Energy Harvesting,* November 2012.

QUADRUPLING CRITICAL CURRENT IN HIGH TEMPERATURE SUPERCONDUCTOR WIRES

Updated: June 20, 2016

PROJECT TITLE:	Superconducting Wires for Direct-Drive Wind Generators	High Performance, Low Cost Superconducting Wires and Coils for High Power Wind Generators
PROGRAM:	Rare Earth Alternatives to Critical Materials (REACT)	
AWARD:	$3,298,424	$5,131,458
PROJECT TEAMS:	Brookhaven National Lab & American Superconductors	University of Houston, SuperPower, Energy2Power & Teco-Westinghouse
PROJECT TERMS:	January 2012 – March 2016	January 2012 – June 2015
PRINCIPAL INVESTIGATOR (PI):	Dr. Qiang Li	Prof. Venkat Selvamanickam

TECHNICAL CHALLENGE

High performance electric machines, such as motors in electric vehicles or generators in wind turbines, require rare earth elements, particularly Neodymium (Nd) and Dysprosium (Dy) for the electric machines' magnetic components. In wind generators, the need for rare earths is quite large (a generator in a wind turbine contains approximately 100 kg of rare earth materials for every MW of rated power) and is still growing, as both the total amount of installed wind capacity and the average size of each individual wind turbine continue to increase. Price fluctuations over the past decade have shown that rare earth materials are sensitive to supply disruptions, and alternative technologies to mitigate or eliminate the dependence of this energy technology on critical rare earth materials would offer risk mitigation for the continued growth of wind power against potential market risks in the future.

TECHNICAL OPPORTUNITY

Using high temperature superconductor (HTS) magnets in wind turbines could dramatically reduce the rare earth requirement compared with traditional permanent magnet (PM) generators (from ~100 kg of Nd and Dy MW in a PM generator to ~100 grams of rare earths per MW in an HTS generator). In addition, HTS generators offer better performance and lower weight for large turbines (see Fig. 1)[24] with corresponding lower operational and capital costs. However, historically the highest performance commercially available HTS wire (Rare earth Element Barium Copper Oxide – (RE)BCO) ranged in cost from $200/kA-m upwards. To be competitive with PM generators, the cost of the HTS conductor must be reduced ~4x, which in turn requires a dramatic increase in the critical current (I_c, the maximum current that a superconductor can sustain)[25]. Advances in materials design and fabrication techniques make it possible to address this challenge by engineering specific defects, known as flux pinning centers, into HTS wires.

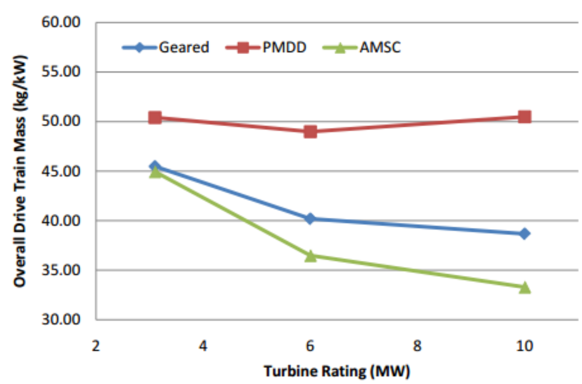

Figure 1. Comparison of overall drivetrain mass for permanent magnet (PM) geared, PM direct drive, and HTS (designed by AMSC) turbines

[24] "Comparative Assessment of Direct Drive High Temperature Superconducting Generators in Multi-Megawatt Class Wind Turbines" B. Maples, M. Hand and W. Musial NREL/TP-5000-49086 www.nrel.gov/docs/fy11osti/49086.pdf (2010)

[25] "Design and Analysis of a 12 MW Superconducting Wind Power Generator", M. Park, International Workshop on Coated conductors for Application 2014, Dec 1 – Dec 3, Jeju, South Korea. (http://www.cca2014.org/)

INNOVATION DEMONSTRATION

ARPA-E funded two teams in the Rare Earth Alternatives in Critical Technologies (REACT) program to develop advanced HTS magnet wire with high critical current: Brookhaven National Lab (teamed with AMSC) and University of Houston (teamed with SuperPower). The teams took different technical approaches to modifying HTS wire composition and structure to address this challenge.

Both teams worked with (RE)BCO wire, which is manufactured commercially by epitaxial deposition of thin films (typically ~1 µm thick) onto buffered substrates on nickel alloy, or steel tape (see Figure 2 for illustration). In magnet applications, the critical current in (RE)BCO films can be improved by introducing defects into the thin film, creating *flux pinning centers* that align and pin magnetic field lines (see Figure 2 for illustration). The fundamental challenge in improving I_c in (RE)BCO for magnet applications is engineering these flux pinning centers to provide the optimal size, concentration, and distribution for the wire in operating conditions, which for HTS generators range from 1-3 T magnetic fields and 30-50 K temperatures.

BNL/ASMC Approach

The BNL/AMSC team combined two approaches to engineeing flux pinning centers for AMSC's (RE)BCO wire. The first approach leveraged nanoscale derivative phases and defects formed during the growth of AMSC's metal organic deposited (MOD) (RE)BCO film. The team identified the optimal concentration of these defects for flux pinning at targeted operating conditions, and altered the design of the growth conditions to consistently produce this microstructure. The new process doubled the critical current. The second approach introduced additional defects through bombardment with high energy ions. The team optimized the ion bombardment conditions and once again doubled the critical current. The ion beam treatment was performed at ion fluxes that are compatible with manufacturing rates on a moving tape.[26] By the completion of the program, the team had demonstrated critical current of >1600 A at 10mm of wire width, for the operating conditions of AMSC's HTS machine design. This represents a >4x improvement over the 400 A/cm width at program start.

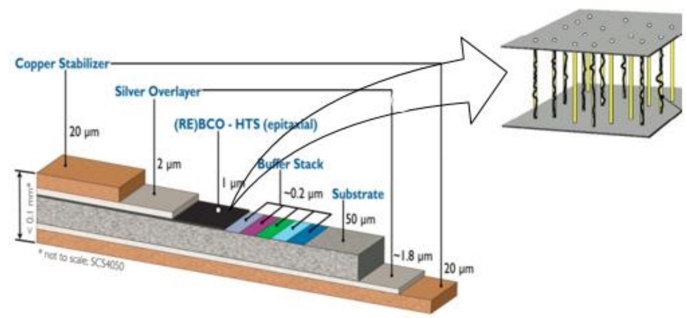

Figure 2. Configuration of (RE)BCO HTS wire (courtesy SuperPower Inc.), (inset: Illustration of flux pinning centers in form of nanocolumns in (RE)BCO film)

UH/Superpower Approach

The UH/SuperPower team built upon SuperPower's chemical vapor deposition (CVD) approach to epitaxial growth of (RE)BCO to introduce flux pinning centers in the form of $BaZrO_3$ nanocolumns. The team tuned the CVD process to produce Zr-doped (RE)BCO films for maximum I_c at the operating conditions of the team's HTS generator design. YBCO doped with 25% $BaZrO_3$ produced the best performance, with $BaZrO_3$ nanocolumns of 5 nm with an average spacing of 15-20 nm, yielding I_c levels greater than 3X over baseline performance prior to the project. The team also developed process improvements to enable the deposition of thicker films without degradation of crystal quality or discontinuities in the $BaZrO_3$ nanocolumns. With the combination of increased flux pinning centers in $BaZrO_3$ nanocolumns and high-quality films through the improved process conditions, the team achieved >4x improvement in I_c at production thickness, resulting in a record critical current density for flux-pinning HTS material. The UH team further demonstrated

[26] Martin W. Rupich, "Performance of AMSC's 2G wire and R&D improvements", HTS4Fusion Conductor Workshop, Pieve S. Stefano, Italy, Sept 11 – 12, 2015.

a critical current of 3900 A with greater thickness through enhanced deposition control. [27] This is a >6x improvement over their 600 A rating at program start for their standard 12 mm width wire.

PATHWAY TO ECONOMIC IMPACT

AMSC has successfully implemented many of the innovations developed in the ARPA-E REACT program into their mainline commercial production, with AMSC completing the upgrades to production line equipment to allow the routine formation of the optimized flux pinning microstructure. The upgrades have resulted in 2X improvement in I_c over pre-program wire.

In March 2016, AMSC formed a strategic partnership with BASF to reduce manufacturing costs of HTS wire. This joint program will couple AMSC's HTS wire technology know-how with BASF's chemical processing expertise to develop potentially low cost manufacturing process at BASF. Success of this program and the involvement of BASF are expected to accelerate acceptance of HTS wire in both cable and coil based HTS applications.

SuperPower has successfully implemented many of the innovations developed in the ARPA-E REACT program into their mainline commercial production as well, with SuperPower implementing 15% doping with $BaZrO_3$ in their magnet wire production. The upgrades have resulted in 2x improvement in Ic over pre-program wire. SuperPower has continued to improve their wire and plans another 50% improvement based on REACT technology by 2017.

Commercial wire from AMSC and SuperPower with ARPA-E technology has been purchased by early adopters including the U.S. Navy (for developmental systems in ship degaussing and protection systems), developers of scientific equipment (such as CERN, Lawrence Berkeley National Lab, and other builders of advanced accelerators) and a variety of other customers around the world.

LONG-TERM IMPACTS

The technologies that can extend performance to 4X improvement for both the BNL/AMSC and UH/SuperPower team have proven to be reliable, robust, tunable to different HTS operating conditions, and compatible with large-scale manufacturing. However, it will take larger sales volumes of HTS wire to fully reap the cost benefits of the innovations that the BNL/AMSC and UH/SuperPower team demonstrated. The sales volumes for niche applications such as those for early adopters in the Navy or in scientific applications have not proven sufficient to support the cost reductions possible and needed for applications in large industrial motors.[28,29]

The demonstration of significantly improved HTS wire properties has removed a significant technical barrier to the development of HTS generators. However, there are still challenges in reliability, maintenance, and lifetime of HTS electric machines. A successful demonstration of a large-scale HTS motor or generator would have far-reaching consequences throughout the energy sector—enabling far higher power ratings for wind turbines of 10 MW[30]; improving efficiency of electric machines such as industrial motors or power plant generators by 2-3%; and potentially even enabling hybrid-electric passenger aircraft[31].

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[27] V. Selvamanickam, M. Heydari Gharacheshmeh, A. Xu, Y. Zhang and E. Galstyan, "Critical current density above 15 MA/cm^2 at 30 K, 3 T in 2.2 µm thick heavily-doped (Gd,Y)$Ba_2Cu_3O_x$ superconductor tapes", *Supercond. Sci. Technol.* **28**, (2015) 072002.

[28] "Analysis of future prices and markets for high temperature superconductors", J. Mulholland, T. Sheahen and B. McConnell, June 2003, ORNL, U.S. Department of Energy. See Table 3, page 15.http://web.ornl.gov/sci/htsc/documents/pdf/Mulholland%20Report%20063003.pdf

[29] Martin W. Rupich, "Scale-up of 2G HTS wire manufacturing at AMSC", DOE annual peer review, Arlington VA, July 29, 2008. http://www.htspeerreview.com/2008/pdfs/presentations/tuesday/joint/joint_2_scale_up.pdf

[30] http://www.boem.gov/Renewable-Energy-Program/Renewable-Energy-Guide/Offshore-Wind-Energy.aspx

[31] Madavan Nateri, "A NASA perspective on electric propulsion technologies for commercial aviation", Large electric machine workshop, University of Illinois at Urbana-Champaign, April 5-6, 2016, http://machineroadmap.ece.illinois.edu/files/2016/04/Madavan.pdf

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of April 2016, the AMSC/BNL team's project has generated 1 invention disclosure to ARPA-E and 1 U.S. Patent and Trademark Office (PTO) patent application. The AMSC/BNL team has also published the scientific underpinnings of this technology extensively in the open literature:

Martin W. Rupich, Srivatsan Sathyamurthy, Steven Fleshler, Qiang Li, Vyacheslav Solovyov, Toshinori Ozaki, Ulrich Welp, Wai-Kwong Kwok, Maxime Leroux, Alexei E. Koshelev, Dean J. Miller, Karen Kihlstrom, Leonardo Civale, Serena Eley, and Asghar Kayani, "Engineered Pinning Landscapes for Enhanced 2G Coil Wire", IEEE Trans. on Appl. Supercond. 26 (2016) 6601904.

S Fleshler, K DeMoranville, J Gannon Jr, X Li, E Podtburg, M W Rupich, S Sathyamurthy, C L H Thieme, D Tucker and L Whitman, "Development Status of AMSC Amperium® Wire", J. Phys: Conf. Series 507, (2014) 022005.

Vyacheslav F. Solovyov, Li-jun Wu, Martin W. Rupich, Srivatsan Sathyamurthy, Xiaoping Li, Qiang Li, "Two-stage epitaxial growth of vertically-aligned SnO_2 nano-rods on (001) ceria", Journal of Crystal Growth, (2014), 107–111.

M. W. Rupich, X. Li, S. Sathyamurthy, C. L. H. Thieme, K. DeMoranville, J. Gannon, S. Fleshler, "Second Generation Wire Development at AMSC", IEEE Trans. on Appl. Supercond. 23 (2013) 6601205.

Vyacheslav F. Solovyov, Qiang Li, Martin Rupich, Srivatsan Sathyamurthy and Xiaoping Li, "New Pinning Strategies for Second-Generation Wires", IEEE Trans. on Appl. Supercond. 23, (2013) 6600905.

As of April 2016, the UH/SuperPower team's project has generated 1 licensed technology and 1 U.S. Patent and Trademark Office (PTO) patent application. The UH/SuperPower team has also published the scientific underpinnings of this technology in the open literature (students' names are underlined):

V. Selvamanickam, M. Heydari Gharahcheshmeh, A. Xu, Y. Zhang and E. Galstyan, "Requirements to achieve high in-field critical current density at 30 K in heavily-doped $(Gd,Y)Ba_2Cu_3O_x$ superconductor tapes", *Supercond. Sci. Technol.* **28,** 104003 (2015).

A. Xu, L. Delgado, M. Heydari Gharahcheshmeh, N. Khatri, Y. Liu, V. Selvamanickam, "Strong correlation between J_c(T, H || c) and J_c(77 K, 3 T || c) in Zr-added (Gd,Y)BaCuO coated conductors at temperatures from 77 down to 20 K and fields up to 9 T" *Supercond. Sci. Technol.* **28**, (2015) 082001.

V. Selvamanickam, M. Heydari Gharacheshmeh, A. Xu, Y. Zhang and E. Galstyan, "Critical current density above 15 MA/cm^2 at 30 K, 3 T in 2.2 µm thick heavily-doped $(Gd,Y)Ba_2Cu_3O_x$ superconductor tapes", *Supercond. Sci. Technol.* **28**, (2015) 072002.

V. Selvamanickam, M. Heydari Gharahcheshmeh, A. Xu, E. Galstyan, L. Delgado and C. Cantoni, "High critical currents in heavily doped $(Gd,Y)Ba_2Cu_3O_x$ superconductor tapes" *Appl. Phys. Lett.* **106,** 032601 (2015).

E. Galstyan, M. Heydari Gharacheshmeh, L. Delgado, A. Xu, G. Majkic, and V. Selvamanickam, "Microstructure Characteristics of High Lift Factor MOCVD REBCO Coated Conductors with High Zr Content" *IEEE Trans. Appl. Supercond.* **25,** 6954395 (2015).

A. Xu, N. Khatri, Y. Liu, G. Majkic, V. Selvamanickam, D. Abraimov, J. Jaroszynski and D. Larbalestier, "Broad temperature pinning study of 15 mol.% Zr-added (Gd, Y)-Ba-Cu-O MOCVD coated conductors", *IEEE Trans. Appl. Supercond.* **25,** 6603105 (2015).

A. Xu, L. Delgado, N. Khatri, Y. Liu, V. Selvamanickam, D. Abraimov, J. Jaroszynski, F. Kametani and D. C. Larbalestier, "Strongly enhanced vortex pinning from 4 to 77 K in magnetic fields up to 31 T in 15 mol% Zr-added (Gd, Y)-Ba-Cu-O superconducting tapes" *APL Materials* **2,** 046111 (2014)

V. Selvamanickam, A. Xu, Y. Liu, N. D. Khatri, C. Lei, Y. Chen, E. Galstyan and G. Majkic, "Correlation between in-field critical currents in Zr-added $(Gd,Y)Ba_2Cu_3O_x$ superconducting tapes at 30 K and 77 K" *Supercond. Sci. Technol.* **27,** 055010 (2014).

V. Selvamanickam, Y. Chen, G. Majkic, T. Shi, Y. Liu, N. D. Khatri, J. Liu, Y. Yao, X. Xiong, C. Lei, S. Soloveichik and E. Galtsyan, "Enhanced critical currents in high levels of Zr-added $(Gd,Y)Ba_2Cu_3O_x$ superconducting tapes", *Supercond. Sci. Technol.* **26,** 035006 (2013)

G. Majkic, Y. Yao, J. Liu, Y. Liu, N. Khatri, T. Shi, Y. Chen, E. Galstyan, C. Lei and V. Selvamanickam, "Effect of High BZO Dopant Levels on Performance of 2G-HTS MOCVD Wire at Intermediate and Low Temperatures", *IEEE Trans. Appl. Supercond.* **23,** 6602605 (2013)

C. Lei, E. Galstyan, Y. Chen, T. Shi, Y. Liu, N. Khatri, J. Liu, X. Xiong, G. Majkic and V. Selvamanickam, "The structural evolution of $(Gd,Y)Ba_2Cu_3O_x$ tapes with Zr addition made by metal organic chemical vapor deposition" *IEEE Trans. Appl. Supercond. 23,* 6602404 (2013)

Y. Liu, Y. Yao, Y. Chen, N. D. Khatri, J. Liu, E. Galtsyan, C. Lei, and V. Selvamanickam, "Electromagnetic properties of $(Gd,Y)Ba_2Cu_3O_x$ superconducting tapes with high levels of Zr addition", *IEEE Trans. Appl. Supercond.* **23,** 6601804 (2013)

V. Selvamanickam, Y. Yao, Y. Chen, T. Shi, Y. Liu, N. D. Khatri, J. Liu, C. Lei, E. Galtsyan and G. Majkic, "Low-temperature, High Magnetic Field Critical Current Characteristics of Zr-added $(Gd,Y)Ba_2Cu_3O_x$ superconducting tapes", *Supercond. Sci. Technol.* **25,** 125013 (2012).

DEVELOPING PASSIVE COOLING TECHNOLOGY

Updated: February 24, 2016

PROJECT TITLE: Photonic Structures for High-Efficiency Daytime Radiative Cooling	
PROGRAM: OPEN 2012	
AWARD: $2,943,851	
PROJECT TEAM: Stanford University (Lead)	
PROJECT TERM: February 2013 – June 2016	
PRINCIPAL INVESTIGATOR (PI): Dr. Shanhui Fan	

TECHNICAL CHALLENGE

Over the past 50 years, the growing use of air conditioning has resulted in a significant increase in the use of electricity and water. In the U.S. today, the electricity required to cool residential and commercial buildings accounts for 6% and 8% of total electricity production, respectively. Additionally, standard air conditioners transfer heat from inside to outside a building, exacerbating external heating that can contribute to the urban “heat island” effect, where the outside ambient temperature is higher than that in surrounding rural areas. Technological innovations in cooling systems are needed to improve energy and water use in buildings, and reduce CO_2 and other harmful emissions associated with cooling.

TECHNICAL OPPORTUNITY

Due to the fact that light and heat are linked, changing the optical properties (such as color) of surfaces can in principle both reflect unwanted heat and help dissipate heat by emitting it in the form of infrared radiation. New advances in materials science and engineering now make it possible to create structured materials tailored to reflect sunlight very strongly while simultaneously emitting infrared light. This enables a concept known as day-time radiative cooling. It has long been known that radiative cooling is possible at night because it transfers heat from relatively warm terrestrial objects to the extreme cold of deep space. But this counter-intuitive concept—that an object under full sun can be made to be cooler than its surroundings—was not practical before the development of new methods that allow the control of the radiative properties of materials.

INNOVATION DEMONSTRATION

Stanford University engineers have invented a novel coating material that can help cool buildings, even on sunny days, by radiating heat away from the buildings and sending it directly into space. The key to Stanford’s cooling approach is to employ a multilayered coating to reflect nearly all the sunlight across the solar spectrum and also emit energy in the mid infrared frequency range between 8 and 13 micrometers— employing a “window” in the atmosphere that allows a thermal connection to deep space. In this way, waste heat is removed from the local environment.

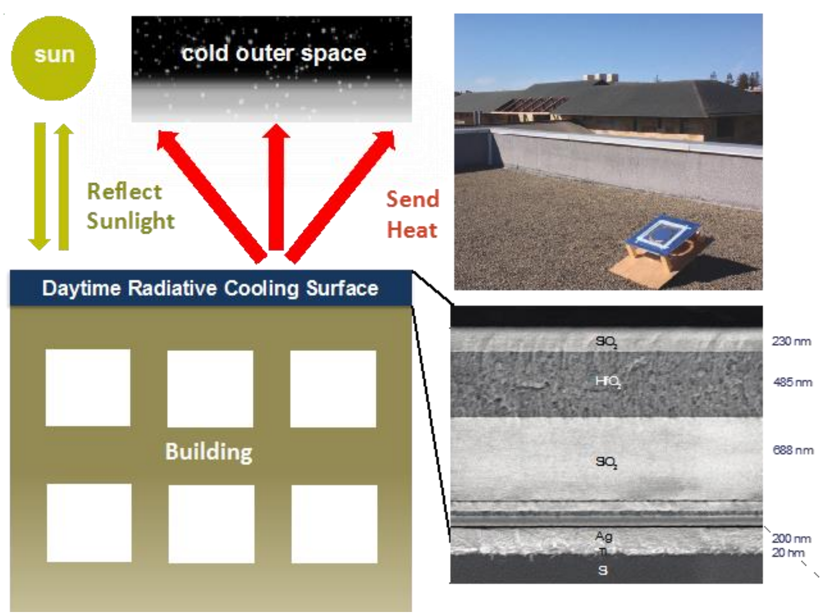

Figure 1. Demonstration of how photonic structures can be used to cool a building, and a picture of an early rooftop test

Stanford University's technology relies on creating structures that tailor the reflection, absorption, and emission of light and heat in nanostructured materials. The multilayered coating is just 1.8 microns thick, about 1/100th the thickness of a human hair. The top three layers (two thicker silicon dioxide (SiO_2) layers separated by a thick hafnium dioxide

(HfO_2) layer) act as the radiator, absorbing heat from below and reemitting the energy at wavelengths that can be emitted back into deep space (between 8 and 13 micrometers).

Stanford University has demonstrated its technology in tests during full solar illumination on a California rooftop and shown that it provides heat rejection of ~40 W/m2, lowering temperatures 3°C to 5°C below the ambient temperature on the rooftop—a remarkable demonstration of this innovative cooling approach.

PATHWAY TO ECONOMIC IMPACT

The Stanford University team's innovation could enable buildings, power plants, solar cells and even clothing to cool without using electric power or loss of water, and without the associated emission of waste heat to the local environment. The Stanford team is now scaling this technology to cool water for use with conventional air conditioners and for direct use in the chilled water loops of office buildings, shopping centers and warehouses.

Further studies of Stanford University's technology to determine specific market applications, either standalone or as part of a complementary cooling system, are ongoing. As an early stage technology, prototype-cooling panels have demonstrated a capability that could change existing cooling approaches, and the pathway to economic impact requires developing first markets and demonstrating system reliability and cost-effectiveness. In recognition of this novel cooling technology, the MIT Technology Review recently named the ARPA-E co-Principal Investigator for Stanford University one of its top 35 innovators under the age of 35[32].

LONG-TERM IMPACTS

Air conditioners in residential and commercial buildings in the U.S. now consume 336,000 GWh of electricity and create annual CO_2 emissions totaling 195 million tons. An initial analysis indicates that the radiative cooling panels that have been developed could save 10-20% of these costs in dry regions, with broader grid-wide benefits of reducing peak electric loads in the middle of the day that are strongly driven by air conditioning.

In addition, there is strong potential for applications in the many situations where cooling affects energy efficiency. For instance, the demonstration of this novel, passive cooling technology by the Stanford University team has led several separately funded groups to propose similar approaches to passive, radiative cooling as part of ARPA-E's new program on Advanced Research In Dry-Cooling (ARID), which addresses the efficiency of thermoelectric power plants where water use for cooling is restricted. Radiative cooling is a promising approach to create a cold-storage reservoir to chill recirculated cooling water.

INTELLECTUAL PROPERTY & PUBLICATIONS

As of February 2016, the Stanford University team's project has generated two invention disclosures with ARPA-E and two U.S. non-provisional patent applications. The team has also published the scientific underpinnings of the technology extensively in the open literature. A list of publications is provided below:

Aaswath Raman, Marc Anoma, Linxiao Zhu, Eden Rephaeli and Shanhui Fan, "Passive Radiative Cooling Below Ambient Air Temperature Under Direct Sunlight", *Nature*, 515, 540-544 (2014).

Linxiao Zhu, Aaswath Raman and Shanhui Fan, "Color-Preserving Daytime Radiative Cooling", *Applied Physics Letters*, 103, 223902 (2013).

Linxiao Zhu, Aaswath Raman and Shanhui Fan, "Radiative cooling of solar absorbers using a visibly-transparent photonic crystal thermal blackbody", Proceedings of the National Academy of Sciences (2015).

Linxiao Zhu, Aaswath Raman, Ken Wang, Marc Anoma and Shanhui Fan, "Radiative Cooling of Solar Cells", *Optica*, 1 (1), 32-38 (2014).

[32] 35 Innovators Under 35 | 2015 | MIT Technology Review. (2015, August 18). http://www.technologyreview.com/lists/innovators-under-35/2015/

ADVANCED MATERIAL FOR ENERGY EFFICIENCY

Updated: February 24, 2016

PROJECT TITLE: Slippery Liquid-Infused Porous Surfaces (SLIPS)	
PROGRAM: OPEN 2012	
AWARD: $1,999,998	
PROJECT TEAM: Harvard University (Lead); Pennsylvania State University	
PROJECT TERM: April 2013 – June 2016	
PRINCIPAL INVESTIGATOR (PI): Dr. Joanna Aizenberg	

TECHNICAL CHALLENGE

A significant portion of U.S. energy use is wasted due to fluid flow problems at the surfaces of machines and conduits. The energy is lost through friction, drag, and wear compounded by contamination, build-up of microorganisms, and corrosion. In fact, at least 5% of the world's energy is wasted due to frictional losses. To address these problems, innovations in materials design are needed to create stable and robust surface coatings that can work in harsh operating environments.

TECHNICAL OPPORTUNITY

Advances in materials science including nanotechnology, computational methods, powerful characterization tools, and biologically-inspired materials design have opened new pathways for technical innovation and the creation of high-performance materials and coatings.

INNOVATION DEMONSTRATION

The project team adapted the strategy that a carnivorous plant uses for creating robust low-friction surfaces. The approach is to create a surface layer that is porous at the nanometer scale, and then fill the pores with a low-friction fluid. To manufacture such coatings economically, the Harvard team developed methods to create low-cost nano-structured coatings on a variety of surfaces.

The team has combined different structured coatings with different fluid fillers, creating a wide range of designed surface properties. The liquid-filled structures repair themselves if scratched or damaged, resulting in stable coatings with the potential to significantly outperform conventional technologies, such as Teflon, in friction and drag reduction and in repelling a broad range of contaminants.

Their robust surface modification and coating process can be adapted for a variety of applications to improve energy efficiency. These applications include refrigeration, shipping, wastewater treatment, industrial cooling systems, and moving materials through pipelines.

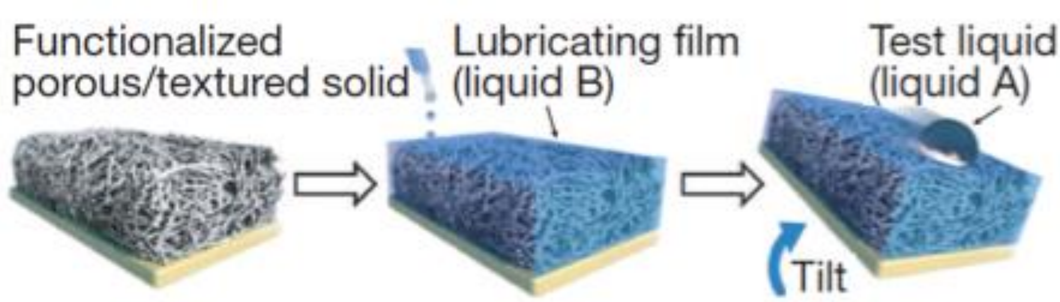

Figure 1. Schematic illustration of the formation of bio inspired low-friction coatings

PATHWAY TO ECONOMIC IMPACT

The Harvard team formed a new company, SLIPS Technologies Inc, which launched in October 2014 after securing venture capital financing. The company is commercializing SLIPS for use in various industrial, consumer, and medical applications. One important energy-focused application they are pursuing is in refrigeration, where SLIPS coatings can significantly reduce energy needed for defrost cycles. The company is engaged with commercial partners to further develop this application.

In parallel, the Harvard team and the company are jointly evaluating a second possible application to create anti-fouling coatings for ships and other marine structures. These coatings will improve fuel efficiency through reduced drag and displace the toxic contaminants that are released from present anti-fouling products.

LONG-TERM IMPACTS

The commercial demonstration of this innovative materials approach to high-performing coatings has reduced the long-term and high-risk technological barriers in the development of an important class of energy-efficient technologies.

The Harvard team's defrosting application is on a promising track to develop viable commercial products and grow in market penetration. This application could save over 2,650 GWh of the annual energy consumed in the U.S. for residential and commercial refrigeration, with a corresponding annual reduction in CO_2 emissions of more than 1.4 million metric tons.

Additional energy applications, which may be commercialized by the Harvard team, or may be developed by other companies who are inspired to create similar approaches, have the potential to economically reduce energy inefficiency in many other applications. Ultimately, this new class of materials is well positioned to support advanced energy technologies that will strengthen U.S. economic and energy security.

INTELLECTUAL PROPERTY & PUBLICATIONS

As of February 2016, the Harvard team's project has generated nine invention disclosures to ARPA-E and four U.S. PTO patent applications. The team has also published scientific underpinnings of the technology extensively in the open literature. A list of publications is provided below:

Cui, J.; Daniel, D.; Grinthal, A.; Lin, K.; Aizenberg, J., "Dynamic polymer systems with self-regulated secretion for the control of surface properties and material healing", *Nat. Mater.* 2015, *14* (8), 790-795.

Daniel, D.; Mankin, M. N.; Belisle, R. A.; Wong, T. S.; Aizenberg, J., "Lubricant-infused micro/nano-structured surfaces with tunable dynamic omniphobicity at high temperatures", *Appl. Phys. Lett.* 2013, *102* (23), 231603-1-4.

Epstein, A. K.; Wong, T. S.; Belisle, R. A. ; Boggs, E. M.; Aizenberg, J., "Liquid-infused structured surfaces with exceptional anti-biofouling performance", *P. Natl. Acad. Sci. USA* 2012, *109* (33), 13182-13187.

Grinthal, A.; Aizenberg, J., "Mobile Interfaces: Liquids as a Perfect Structural Material for Multifunctional, Antifouling Surfaces", *Chem. Mater.* 2014, *26* (1), 698-708.

Hou, X.; Hu, Y.; Grinthal, A.; Khan, M.; Aizenberg, J., "Liquid-based gating mechanism with tunable multiphase selectivity and antifouling behavior", *Nature* 2015, *519* (7541), 70-73.

Howell, C.; Vu, T. L.; Johnson, C. P.; Hou, X.; Ahanotu, O.; Alvarenga, J.; Leslie, D.; Uzun, O.; Waterhouse, A.; Kim, P.; Super, M.; Aizenberg, M.; Ingber, D. E.; Aizenberg, J., "Stability of Surface-Immobilized Lubricant Interfaces under Flow", *Chem. Mater.* 2015, *27* (5), 1792-1800.

Howell, C.; Vu, T. L.; Lin, J. J.; Kolle, S.; Juthani, N.; Watson, E.; Weaver, J. C.; Alvarenga, J.; Aizenberg, J., "Self-Replenishing Vascularized Fouling-Release Surfaces", *ACS Appl. Mater. Interfaces* 2014, *6* (15), 13299-13307.

Kim, P.; Kreder, M. J.; Alvarenga, J.; Aizenberg, J., "Hierarchical or Not? Effect of the Length Scale and Hierarchy of the Surface Roughness on Omniphobicity of Lubricant-Infused Substrates", *Nano Lett.* 2013, *13* (4), 1793-1799.

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FAST X-RAY SORTING FOR RECYCLING LIGHT METALS

Updated: July 18, 2016

PROJECT TITLE: Low-Cost High Throughput In-Line X-Ray Fluorescence Scrap Metal Sorter	
PROGRAM: Modern Electro/Thermochemical Advances in Light Metals Systems (METALS)	
AWARD: $2,021,189	
PROJECT TEAM: UHV Technologies (Lead); Phinix, LLC; OmniSource Corporation	
PROJECT TERM: January 2014 – September 2016	
PRINCIPAL INVESTIGATOR (PI): Dr. Nalin Kumar	

TECHNICAL CHALLENGE

Reducing automobiles' weight by using more aluminum and other light metals in their construction is an effective way to improve fuel efficiency. In principle, lighter cars and better fuel economy are global benefits. However, there is a challenge with these cars at their end-of-life. Many different light metal alloys are used in cars, and they must be accurately separated during recycling to preserve their strength and economic value. The problem is magnified because the alloys can be difficult and expensive to separate. For instance, the aluminum alloy used in a car frame differs by only a few percent from the alloy used in the car's body. Cost-effective separation and recycling of the different alloys could dramatically reduce the cost of light metals and lower the environmental impact of manufacturing with them. To be commercially attractive, a sorting system should be able to evaluate 10 pieces of scrap per second, and the sorting should cost less than about 2 cents per pound of accurately sorted material.

TECHNICAL OPPORTUNITY

Currently, aluminum alloy scrap is sorted by hand, using a special X-ray fluorescence (XRF) gun. With this gun, a worker shines X-rays at a piece of scrap metal, and measures the energy spectrum of the X-rays emitted back from the scrap's surfaced to determine the type of alloy. This process can take up to a minute for a single piece of scrap. This is due both to the low intensity of the X-ray source and the inconsistency when sorting thousands of metal pieces by hand. One of the difficulties in automating XRF sorting of metal alloys is that the X-rays currently come from "point" sources like those used for medical X-rays. Point sources emit X-rays from small regions, which is needed for good quality medical X-ray images, but yields a low intensity over the large areas needed for industrial sorting. As a result, automating sorting systems requires a mechanical positioning systems built into the X-ray source, which is costly and slow. New proprietary X-ray tube technology, X-ray optics, position sensitive detection, and rapid data acquisition and analysis systems now make it possible to address these problems.

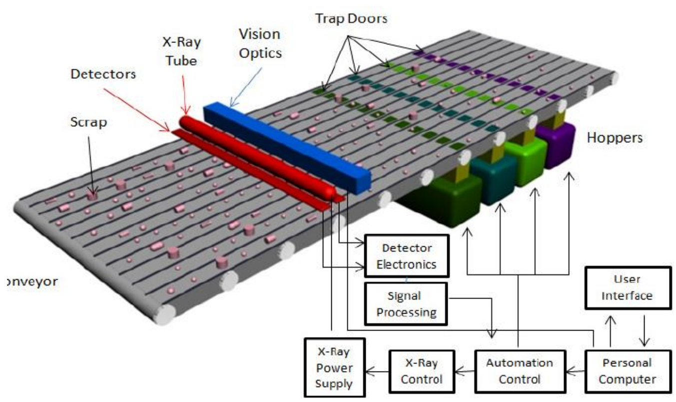


Figure 1. Schematic diagram of the sorter. The long linear X-ray source bombards up to 12 scrap pieces simultaneously, the emitted fluorescence X-rays are measured for more than 10 elements to determine alloy composition of each piece. The pieces are then sorted in to their appropriate containers using a combination of XRF data and a vision system

INNOVATION DEMONSTRATION

Working within the METALS program, UHV Technologies set out to develop a high throughput, fully automated sorter for light metal alloys, as illustrated in Figure 1. To accomplish this, the company addressed three major challenges: (i) developing a high intensity, linear X-ray tube for parallel elemental composition measurement on a tenth of a second time scale; (ii) developing low cost X-ray optics and silicon detector arrays to continuously resolve real time XRF signals from at least 10 elements (Al, Mg, Si Ti, Cu, Fe, Cr, Ni, Mn, Zn) with sufficient sensitivity to distinguish different alloy compositions; and (iii) developing intelligent software to correlate the XRF data with optical images to identify the unique elemental composition signature for each piece of scrap.

UHV has developed a linear X-ray tube (Figure 2, top panel) which uniformly illuminates the entire width of the conveyer with X-rays. This innovative X-ray source reduces the tube power requirements by a factor of 10, thereby reducing cost, and enhancing reliability and lifetime. This source contains no moving parts, and is simple enough that the source can be overhauled on-site by a technician, rather than returned to the manufacturer for refurbishment.

Figure 2. (top) 30 kV, 36” wide X-ray source. (bottom) The UHV pilot scale aluminum alloy sorting system

The detector system has been constructed using multiple arrays of commercial silicon avalanche photodiodes, paired with proprietary X-ray optics to record spatially resolved X-ray fluorescence spectra. The team has demonstrated the ability to discriminate and quantify the concentrations of Al, Mg, Si, Ti, Cr, Fe, Ni, Cu, Mn and Zn with accuracies better than 99%.

The project team has developed software that uses the array of fluorescence spectra evolving in real time to match each piece passing underneath the X-ray system with the fluorescence fingerprint of an alloy. This software is the first of its kind, able to analyze the shape and reflectance of each metal piece, determine the best place to analyze it, and then use standard spectra to identify, and send instructions to the sorting hardware for correct alloy shunting in milliseconds. Software also calculates the percentage and weight of each element in a batch of sorted scrap ready for melting during recycling. This avoids an extra melting step in current recycling process resulting in an additional 5-8 cents/lb reduction in overall costs.

In a double-blind test, the proof-of-concept system has demonstrated a better than 99% sorting accuracy, including the ability to separate 5000 and 6000 series aluminum alloys. This has been repeated in real-world testing at an automotive scrap sorting facility. The team has demonstrated separation of 5xxx and 6xxx automotive alloy scrap at speeds exceeding 120 ft/min and a potential throughput of 40 million pounds/year, using a medium scale commercial prototype designed and constructed during this project.

PATHWAY TO ECONOMIC IMPACT

The project team has carried out extensive techno-economic analysis and supply-chain customer discovery. UHV’s system, incorporating its new linear X-ray source and automated processing, can enable businesses to profitably sort light metal alloy pieces, and to improve the sustainability of the light metal industry.

UHV has established commercial connections and an agreement for field-testing a prototype unit in a commercial setting. In May 2016, UHV installed its first test sorting line with a potential throughput of 40 million lbs/year at an industrial partner’s (OmniSource) scrap processing yard. UHV’s pilot installation has been used to test the system’s throughput and reliability under actual industrial conditions. The pilot phase for this work will be completed in 2016, and negotiations for scale up to a full industrial installation are ongoing.

LONG-TERM IMPACTS

UHV's sorting diagnostics provide a commercial option to reduce energy consumption and costs associated with manufacturing light metal components from recycled light metal scrap that is typically discarded or downgraded by blending. As few as 30 metal sorting lines using UHV technology would sort most of the scrap generated in the U.S. Two million tons of these light metals would no longer need to be exported for hand sorting, with the potential to expand the revenue of the U.S. light metal recycling industry by $120 million/year.

MICRON-SCALE THERMOLECTRICS FOR IMPROVED ENERGY EFFICIENCY

Updated: June 27, 2016

PROJECT TITLE: Advanced Semiconductor Materials for Thermoelectric Devices	
PROGRAM: OPEN 2009	
AWARD: $3,000,000	
PROJECT TEAM: *Phononic (Lead)*, Oklahoma State University, Purdue University, Caltech	
PROJECT TERM: December 2009 – March 2012	
PRINCIPAL INVESTIGATOR (PI): Dr. Anthony Atti	

TECHNICAL CHALLENGE

Residential and commercial building cooling represents over 4% of U.S. energy consumption, an over $100 billion dollar market opportunity. It is currently addressed primarily through passive cooling, e.g. fans, rather than by active thermal management. The current state-of-the-art is represented by vapor compression cycles, which do not scale to small size effectively and use greenhouse gases such as chlorofluorcarbons (CFC), hydrochlorfluorcarbon (HCFC), and hydrofluorcarbons (HFC) as their working fluid, posing an enormous emission impact if they should leak. Waste heat from transportation, power generation, and industrial processes represents over 50% of U.S. energy consumption, but its recovery has been economically unachievable. Both of these enormous opportunities could be addressed using thermoelectric materials and devices. Thermoelectric materials convert heat to electricity, or an electrical current into a heat current, via an intrinsic material phenomenon known as the Seebeck effect. Because the energy conversion is fundamental to the material rather than a device property, these solid-state converters have multiple advantages over state-of-the-art—scalability, compactness, controllability, and robustness. However, their low performance and a dependence on critical materials such as tellurium has prevented their widespread commercial implementation into these markets.

TECHNICAL OPPORTUNITY

Achieving higher device performance requires improvement in the quality of material deposition, allowing the commercial implementation of recent advances in thermoelectric material performance. Decreasing the quantity of critical materials used requires reducing the size of thermoelectric elements. This is theoretically possible but presents engineering challenges for device integration—particularly in making high quality electrical and thermal contacts. Thermoelectric device performance is frequently half of that predicted purely by material properties. Most existing commercial thermoelectric devices are based on technologies and innovations made as early as the 1950s. Over the last twenty years, there has been an enormous improvement in ability to control uniformity of synthesis and microstructure of thermoelectric materials, providing as high as a factor of two increases in thermoelectric performance. The semi-conductor industry has developed and reduced the cost of molecular beam epitaxy (MBE) to enable products such as LEDs and solar cell coatings. This then allows for micron scale control of the chemistry of a thermoelectric module, allowing multiple compositions to be combined into a single thermoelectric leg, further improving performance.

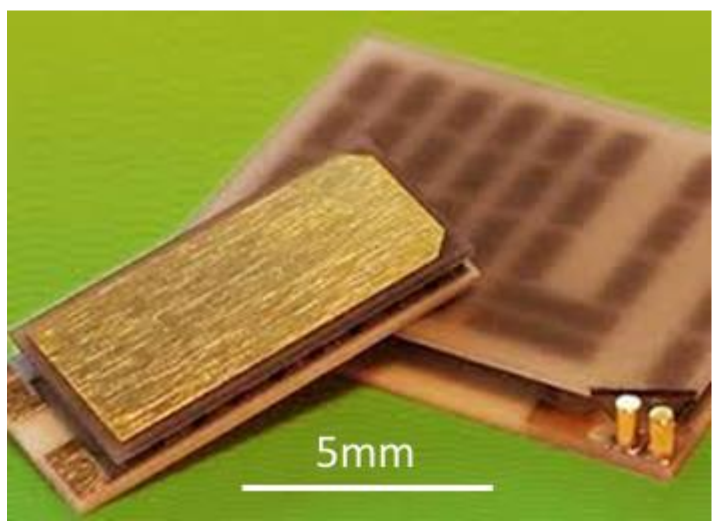


Figure 1. Phononic's thermoelectric devices have demonstrated industry-best performance as high power density, high efficiency solid-state coolers

Because MBE is a micron-scale process, it allows miniaturization of the thermoelectric legs, reducing by orders of magnitude the quantity of critical materials required to manufacture them. Phononic was funded by ARPA-E to combine these advances and thereby demonstrate a device with revolutionary performance.

INNOVATION DEMONSTRATION

Under its OPEN 2009 award from ARPA-E, Phononic's goal was to develop compact and efficient thermoelectric waste heat converters and coolers based on lead chalcogenide materials using molecular beam epitaxy (MBE). The company's primary project goals were (1) high quality deposition thermoelectric materials by MBE, allowing multiple materials to be layered to a thickness of 20 microns, and demonstrating material performance competitive or better than comparable bulk synthesized samples, (2) integration of the MBE legs into a device, demonstrating contact resistances below 25 μΩ-cm-2, (3) demonstrate efficient thermoelectric performance for automotive waste heat conversion, showing a 13% efficiency with 600K hot side temperature, and (4) demonstrate a cooler coefficient of performance of 2.0 for cooling from 350K to 275K. Both (3) and (4) represented a doubling of performance compared to state of the art thermoelectric devices.

Under the award Phononic achieved success in MBE of thermoelectric materials, demonstrating the ability to layer materials up to 20 microns thick with performance comparable to the best of other thin film approaches. Phononic succeeded in meeting its device goals of low electrical contact resistance. Phononic, during the course of the award, did not achieve the goals of unparalleled device performance, but they were able to meet the performance targets of state-of-the-art materials in the improved format of sub-millimeter material devices. Also, its market analysis indicated a much stronger business development case for refrigeration and air conditioning than for waste heat convertors. Consequently, Phononic has focused its efforts in delivering products to these markets.

PATHWAY TO ECONOMIC IMPACT

The success of its ARPA-E award enabled Phononic to achieve significant follow-on funding. The company has now received $75 million in follow-on funding and currently employs over 100 people. The majority of Phononic employees work in the company's manufacturing center in North Carolina. Phononic has made significant technical advances in the engineering and manufacturing of its thermoelectric devices, which are leveraged in its advanced heat transports systems to deliver diverse range of heating and cooling products. This diverse set of customers requires a wide array of heat pumping and energy usage constraints. Phononic, taking advantage of the small package size and modularity of thermoelectric devices, has developed an applications team that designs the system around its customer's requirements.

Phononic is addressing the market of hot spot cooling for high power fiber optics, taking advantage of the high power densities that its sub-millimeter devices can achieve. The company has also entered into the wine and hospital refrigerator markets, which benefit from the advantages only a thermoelectric cooling systems can provide such as low noise, no vibration, and exact and uniform temperature control. This is accomplished while also delivering energy usage that is on par or better than that of a vapor-compression cycle system on the market currently. Phononic is currently beginning to address the small climate control market. As this market was previously closed to thermoelectric cooling due to cost and efficiency concerns, this demonstrates concretely its technical success.

LONG-TERM IMPACTS

Phononic has demonstrated the ability to manufacture full systems based high performance thermoelectrics at a commercially attractive cost. This fundamentally decreases the reliance of thermoelectric conversion and critical materials. Its devices have high power density, making them more compact and therefore more easily integrated into commercial applications. Technological advance is still needed for thermoelectric materials that are cost-competitive for waste heat conversion and the broad-scale refrigeration market. Phononic's technology de-risks the integration of future high performance materials into thermoelectric modules, significantly improving the commercialization pathway of future highly efficient thermoelectric materials. Phononic's work and technical success is therefore a foundation to address the multi-quad energy efficiency opportunities for thermal management and waste heat conversion.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of June 2016, the team's project has generated 3 subject inventions, 3 non-provisional U.S. patent applications, and 3 U.S. Patent and Trademark Office patents.

"*Thin-film heterostructure thermoelectrics in a group IIA and IV-VI materials system*," (10/22/2013) Patent No 8,563,844, Washington, DC: U.S. Patent and Trademark Office.

"Thin-film heterostructure thermoelectrics in a group IIa and IV-VI materials system," (12/2/2014) Patent No 8,901,612, Washington, DC: U.S. Patent and Trademark Office.

"Scanning measurement of Seebeck coefficient of a heated sample," (4/19/2016) Patent No 9,316,545, Washington, DC: U.S. Patent and Trademark Office.

AN ADVANCED COOLER WITH BENIGN REFRIGERANTS

Updated: June 6, 2016

PROJECT TITLE: Free-Piston Zero Emissions Refrigeration (FREEZER™)	
PROGRAM: Building Energy Efficiency Through Innovative Thermodevices (BEETIT)	
AWARD: $3,000,617	
PROJECT TEAM: Infinia Technology Corporation (ITC)	
PROJECT TERM: September 2010 to March 2016	
PRINCIPAL INVESTIGATOR (PI): Mr. Barry Penswick	

TECHNICAL CHALLENGE

New and more efficient cooling methods are needed to reduce the energy consumption and environmental impacts of residential, commercial, and industrial space cooling and refrigeration. Air conditioning accounts for about one-sixth of U.S. electricity demand[33], while refrigeration equipment at homes and businesses consumes more than 1.1 quadrillion British thermal units (BTU) per year. Adding to the environmental challenge, the refrigerants typically used in freezers are potent greenhouse gases (GHG) with atmospheric heat trapping potential thousands of times that of CO_2. Even well-engineered systems leak refrigerant over time: a typical supermarket freezer system in the United States, for example, can contain 3,000 to 6,000 pounds of refrigerant and lose 10% to 25% of its charge annually. Cooling is also an economic and competitive challenge, as it can comprise 50% to 70% of a supermarket's energy costs.[34]

TECHNICAL OPPORTUNITY

Stirling cycle machines have a theoretical coefficient of performance (a measure of cooling system efficiency) as high as 13 (for typical air-conditioning temperatures), roughly 4 times greater than the U.S. Department of Energy's recently upgraded minimum energy efficiency standard. In contrast to other emerging cooling or refrigeration technologies, they use conventional materials and manufacturing processes, and can be adapted to use non-toxic, non-flammable, and low-to-zero global warming potential (GWP) refrigerants such as helium.

The key to unlocking the high efficiency potential of the Stirling cycle lies in maximizing the efficiency with which the heat is exchanged, or pumped, between the hot and cold sides of the cooler, allowing for the maximum potential external temperature drop. To date a major fraction of the hot-to-cold cycle temperature drop has been lost internally in the device's heat

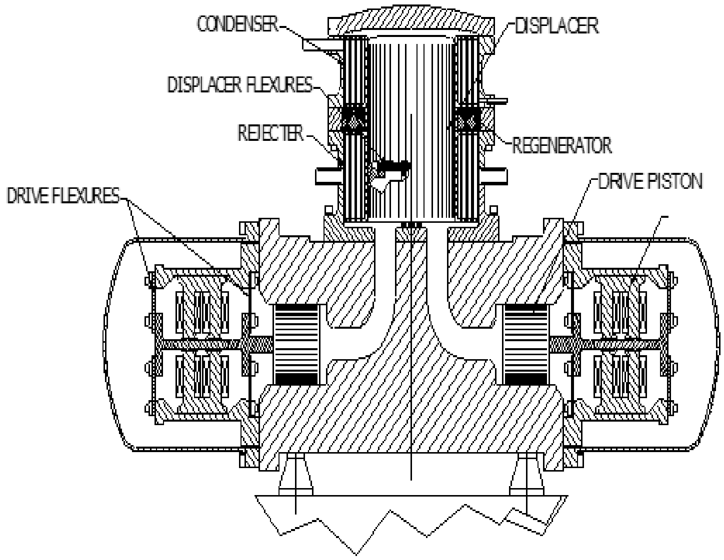


Figure 1. Stirling cycle free piston freezer. The linear piston assembly (the horizontal cylindrical structure) creates a cyclic pressure wave that couples to the driver in the cold-head (the vertical cylindrical structure)

[33] Energy Information Administration, "The South anchors growth in use of electricity for air conditioning since 1993." Today in Energy, 15 Aug 2013. Viewed on 5/4/16 at http://www.eia.gov/todayinenergy/detail.cfm?id=12551

[34] Carbon Trust, *Chilling energy costs.* London: 2012, pg. 3. Viewed 5/4/16 at https://www.carbontrust.com/media/51754/ctg808-energy-savings-retail-interactive.pdf

exchangers, effectively depriving Stirling machines of the large temperature swings that they require to run at peak efficiency.

Recent developments of Stirling engines for space applications and for concentrated solar power systems have improved the technology. The resulting optimization of the base engine design, although configured for electricity production, provides a platform for the development of Stirling-based coolers. The Stirling configuration, in turn, provides the opportunity to replace existing high-GWP refrigerants used in vapor-compression-based systems with non-toxic, low (or zero) GWP refrigerants.

INNOVATION DEMONSTRATION

The original goals for this project were to create a small-scale (12,000 BTU/hr) air conditioning system that uses low GWP refrigerants while delivering a high COP at competitive cost. ITC began with a model-based technical and economic analysis to create a blueprint for the commercialization of the Stirling-based device. ITC used computational models to optimize its innovative heat exchanger design, incorporating heat pipes and, later, thermosiphons. Although the team was able to use ITC's core Stirling technology, the system required substantial modification for the transformation to the cooling configuration, with its small ΔT, and its requirement for green refrigerants.

As the designs for air conditioning applications matured, Technology-to-Market activities and initial testing revealed improved energy efficiency with the potential for use in military cooling applications. As a result, ITC has continued to develop a Stirling air conditioner for use in extreme environments under joint DoD-ARPA-E program. For commercial markets, there is clear potential to deliver value in other applications that have higher temperature differences, such as refrigeration. Under these conditions, the coefficient of performance has shown the potential to reach 1.4 at higher ambient temperatures, which is an improvement over that of existing refrigeration systems. Coupled with the substantial benefit of not using harmful synthetic refrigerants, ARPA-E and ITC agreed to modify ITC's award to include the parallel development of systems for commercial freezers for food service. The target COP was set to 1.4 in a 24,000 BTU/hr refrigeration system.

ITC designed and implemented a prototype refrigeration unit, which uses helium as the working fluid and a CO_2-based external heat transfer loop. ITC has engaged a commercial refrigeration equipment company to assist in commercialization and tested the unit at that company's facilities in late 2015. The results demonstrated a baseline COP of 1.0 with technical pathways identified to increase COP to the target value of 1.4. In addition, the system displayed other traits desirable to refrigeration customers. These include very quiet operation, the ability to be deployed in modular fashion (limiting complex networks of pipes within a store), highly efficient and infinitely variable partial load operation, and rapid temperature pull-down (which maintains safe freezer interior temperatures when the freezer door is repeatedly opened and closed, as in retail applications).

PATHWAY TO ECONOMIC IMPACT

ITC is working with its commercial partner to take the project to the next stage of development. The first step will be to redesign the system to improve its performance and to reduce the overall system cost. Thereafter ITC will fabricate, assemble, and test three additional coolers which will undergo laboratory and field testing at prospective customers' sites in the food service industry. The commercial partner will recruit the test customers, conduct a detailed cost study and undertake major pre-production tasks, such as design for manufacturing and assembly, production part analysis, and distribution and service channel development.

LONG-TERM IMPACTS

This project has demonstrated the potential for a commercially viable refrigeration system that is an innovative alternative to conventional refrigerant-based vapor compression systems, without the use of high-GWP refrigerants and without compromises in energy efficiency. Success in applying the system to refrigeration has the potential to enable future development of the ITC system as an air conditioner as well, with significant potential to cut costs, improve human thermal comfort, and reduce greenhouse gas emissions.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of May 2016, the ITC team has generated protect data held confidentially by ITC. This protected data and other restricted data of ITC and its commercial partner is subject to a Joint Development Agreement. The ITC team has also received media attention related to this technology, as shown below:

Stephen J. Mraz, Infinia uses Stirling cycle for solar power and air conditioning, (8/11/2011) *Machine Design* *[http://machinedesign.com/article/infinia-uses-stirling-cycle-for-solar-power-and-air-conditioning-0811]*

ADDENDUM:
ARPA-E CHALLENGES WHAT'S POSSIBLE: STATIONARY (GRID) ENERGY STORAGE

February 2016

Advanced energy storage promises to play a key role in the modernization of our nation's electricity grid. While relatively little storage is deployed on today's grid, low-cost, high-performance energy storage can not only enable the integration of increasing amounts of renewables, but also improve the grid's operating capabilities, enhance reliability, allow deferral of infrastructure investments, and provide backup power during emergencies. The largest type of grid storage today is pumped hydro, which is low in operational cost, but only feasible in limited geographical regions. Electrochemical storage (batteries) has the potential to provide flexible grid-scale storage, if enhanced performance and lower cost can be achieved. When ARPA-E began supporting innovation in grid storage in 2009, so few electrochemical grid storage systems were installed that cost data was often sparse and highly variable. However, based on available cost estimates for all-vanadium flow and Li-ion battery systems in 2010, ARPA-E estimated that a ten-fold reduction in cost was required to enable disruptive impact of grid-scale electrochemical energy storage. The Agency therefore set aggressive techno-economic goals for new storage technologies.

Since 2009, ARPA-E has invested more than $85 million in research and development of potentially transformative approaches to create new designs, exploit known battery chemistries in new ways, and develop new battery chemistries. A diversified portfolio of new approaches has resulted, the most successful of which have demonstrated the potential for low capital cost ($100/kWh installed at the pack level for batteries) and long cycle life (two major factors in energy storage cost), with performance characteristics suitable for a range of grid services, including leveling the variability in capacity. The more mature teams have already begun moving new types of storage batteries into the market, where they are providing evidence of the performance and economic benefits needed to incentivize their rapid uptake.

CONTENTS

APPENDICES

I. Technical and Economic Criteria for Electrochemical Grid Storage

The U.S. electric grid is a synchronized system that must balance the supply of and demand for electricity over time periods from seconds to days and deliver electricity consistently under a tremendous range of environmental conditions. Over the century of its development, grid evolution has shifted progressively from issues of affordability, accessibility, and safety to cleanliness, reliability, and resiliency. To accommodate these changing needs and to support substantial integration of intermittent renewable sources and distributed generation, the 21st century electric grid must become significantly more flexible. Energy storage is a critical technology for enabling this flexibility and electrochemical energy storage (batteries) offers a diverse set of storage solutions. A more significant discussion of the needs and approaches to grid-scale energy storage is provided in Appendix B.

When ARPA-E launched focused efforts to fund electrochemical storage concepts in 2010, stationary (grid) electrochemical storage solutions[35] were lagging behind those developed for transportation purposes (i.e., electric and hybrid vehicles), which had already been the object of the Department of Energy's (DOE) focus for many years. While lithium-ion (Li-ion) batteries had become quite robust and affordable for consumer electronics and enabled early vehicle applications, the available grid battery storage options were limited to the mature lead-acid (PbA) and sodium-sulfur (NaS) and some early demonstrations of Li-ion chemistries. For stationary storage, the requirements for energy density (both volumetric and by mass) are less stringent than those for vehicle applications, allowing a broader range of battery chemistries, and architectures to be considered. Exploration of this wider technology space has resulted in a dynamic, competitive market place of potential grid-level battery possibilities. Understanding of the techno-economic boundaries, and potential first markets for such batteries has been evolving rapidly over the past five years.

The single largest obstacle to the wider deployment of batteries for stationary storage purposes has been their high capital cost (in \$/kWh), especially when compared with conventional pumped hydro[36] (a typical comparison because of the maturity, wider deployment, and low operational costs of pumped hydro storage systems). As recently as 2010, so few grid storage systems were installed that cost data was often sparse and highly variable. A study by the Electric Power Research Institute (EPRI)[37] provided estimates of battery storage costs at the time. According to EPRI's study, the total system costs[38] of advanced PbA, all-vanadium, and Li-ion battery energy storage were estimated at \$400-\$950/kWh, \$910-\$1250/kWh and \$950-\$1900/kWh, respectively (all for a power range of 100kW-1.2MW and 2-5 hour duration).

The baseline for defining techno-economic requirements for electrochemical storage solutions focuses on large-scale and long-term storage, analogous to that provided by pumped hydro. ARPA-E uses a baseline analysis (Equation 1) to quantify the relative cost target needed for economic uptake:

$$Cost\ per\ Storage\ Cycle\,(\$/kWh_e) = \frac{Energy\ Storage\ Cost\,(\$/kWh)}{Cycles\,(\#)\times Round\ Trip\ Efficiency\ (\%)} \qquad (1)$$

Here the Cost per Storage Cycle is a metric for the added cost for storing electrical power. This is a useful metric for comparing the relative contribution to the cost of electricity that would be created by different types of storage. It omits

[35] The largest battery-based installation in 2010 was a 10 MW/40 MWh lead-acid battery system in Chino, CA that was built in 1988 for load leveling purposes, with a few other systems of power ranging from 3 to 10 MW. However, the limited cycle life (of around 1000 cycles) and high maintenance needs of lead-acid batteries significantly increased their overall cost relative to conventional pumped hydro storage (by some two orders of magnitude) and even relative to other battery technologies. One then alternative, nickel-metal hydride batteries, while having longer cycle life, has high costs associated with some of the metals used, propensity to overcharge, and overall toxicity of some components, which significantly limited their deployment.

[36] See appendices B and D for more information about pumped hydro.

[37] EPRI, *Electricity Energy Storage Technology Options,* Report 1020676, December 2010.

[38] Battery system costs also include cost of power electronics, installation, and other balance of plant components.

additional costs, such as the Internal Rate of Return (IRR) and installation costs that may be similar for different battery systems[39]. A target storage technology capital cost of \$100/kWh corresponds to a cost per storage cycle value of \$0.025/kWh_e for a storage round-trip efficiency of 80%, and 5000-cycle lifetime. This is an aggressive base cost goal, though other, short duration types of grid services such as back-up power, frequency regulation and peak shaving, may support higher costs.

As one can see from Equation 1, installed cost and number of cycles are equally important for the cost reduction. Therefore, ARPA-E efforts were focused on development of new low cost chemistries first and the increase of cycle life second. Based on this initial techno-economic analysis, ARPA-E set the goals shown in the textbox for a focused effort on potentially transformational grid storage technologies under its Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) program40. The \$100/kWh for the installed capital and \$0.025/kWh per storage cycle goal was based on projected cost for wide renewable penetration into utility markets, which provides storage capacity that can balance long-term variations in supply and demand.

ARPA-E Stationary Storage Programmatic Goals:

- ***Capital cost of battery storage < \$100/kWh***
- ***5,000 charge and discharge cycles*** with degradation below 20% in performance, which represents ***10 years of system life***
- ***Roundtrip efficiency of >80% per cycle***
- Scalability to grid-scale GW of power and GW-hr of energy capacity, with ability to ***ramp up to full power in <10 min and operate for >60 min*** at the rated power
- Cost of storage per cycle below \$0.025/kWh

There is in addition a wide range of ancillary services, illustrated in Table 1 that can be provided by storage options with different power and energy capabilities. The market value of some of the ancillary services, can support higher storage costs, and thus provide both a first market for grid storage and a pathway to underwriting the costs of capacity services, which ultimately are in greater need (see Appendix C).

[39] R.M. Darling, et al. "Pathways to low-cost Electrochemical energy storage," Energy and Environmental Science 7, 3459 (2014).

[40] GRIDS program description: **http://arpae.energy.gov/sites/default/files/documents/files/GRIDS_ProgramOverview.pdf**

Table 1: Wide-Ranging Applications of Electrochemical Storage Technologies: Rich and Diverse Solutions for the Electric Grid

Application	Description	Size	Duration	Cycles	Desired Lifetime
Wholesale Energy Services	Arbitrage	10-300 MW	2-10 hr	300-400/yr	15-20 yr
	Ancillary services [2]	See note 2	See Note 2	See Note 2	See Note 2
	Frequency regulation	1-100 MW	15 min	>8000/yr	15 yr
	Spinning reserve	10-100 MW	1-5 hr		20 yr
Renewables Integration	Wind integration: ramp & voltage support	1-10 MW distributed 100-400 MW centralized	15 min	5000/yr 10,000 full energy cycles	20 yr
	Wind integration: off-peak storage	100-400 MW	5-10 hr	300-500/yr	20 yr
	Photovoltaic Integration: time shift, voltage sag, rapid demand support	1-2 MW	15 min-4 hr	>4000	15 yr
Stationary T&D Support	Urban and rural T&D deferral. Also ISO congestion mgt.	10-100 MW	2-6 hr	300-500/yr	15-20 yr
Transportable T&D Support	Urban and rural T&D deferral. Also ISO congestion mgt.	1-10 MW	2-6 hr	300-500/yr	15-20 yr
Distributed Energy Storage Systems (DESS)	Utility-sponsored; on utility side of meter, feeder line, substation. 75-85% ac-ac efficient.	25-200 kW 1-phase 25-75 kW 3-phase Small footprint	2-4 hr	100-150/yr	10-15 yr
C&I Power Quality	Provide solutions to avoid voltage sags and momentary outages.	50-500 kW	<15 min	<50/yr	10 yr
		1000 kW	>15 min		
C&I Power Reliability	Provide UPS bridge to backup power, outage ride-through.	50-1000 kW	4-10 hr	<50/yr	10 yr
C&I Energy Management	Reduce energy costs, increase reliability. Size varies by market segment.	50-1000 kW Small footprint	3-4 hr	400-1500/yr	15 yr
		1 MW	4-6 hr		
Home Energy Management	Efficiency, cost-savings	2-5 kW Small footprint	2-4 hr	150-400/yr	10-15 yr
Home Backup	Reliability	2-5 kW Small footprint	2-4 hr	150-400/yr	10-15 yr

1. Size, duration, and cycle assumptions are based on EPRI's generalized performance specifications and requirements for each application, and are for the purposes of broad comparison only. Data may vary greatly based on specific situations, applications, site selection, business environment, etc.
2. Ancillary services encompass many market functions, such as black start capability and ramping services, that have a wide range of characteristics and requirements.

Source: DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, Sandia Report (Feb 2015).

Understanding the costs of battery storage remains a difficult challenge, because costs are reported in a variety of different ways. A breakdown of some of the different levels of integration of both transportation (EV batteries) and stationary (grid storage batteries) is shown in Figure 1. Reported costs often do not differentiate the costs for cells, which are integrated with significant cost addition into packs containing multiple cells. For grid-level storage, a full pack may involve integration of multiple sub packs with associated additional controls (battery management system, BMS) and enclosure. Additional costs for AC/DC power conversion, right of the way, site preparation, and installation also contribute to the full system cost for grid level storage, and are generally not clearly differentiated in reporting[41].

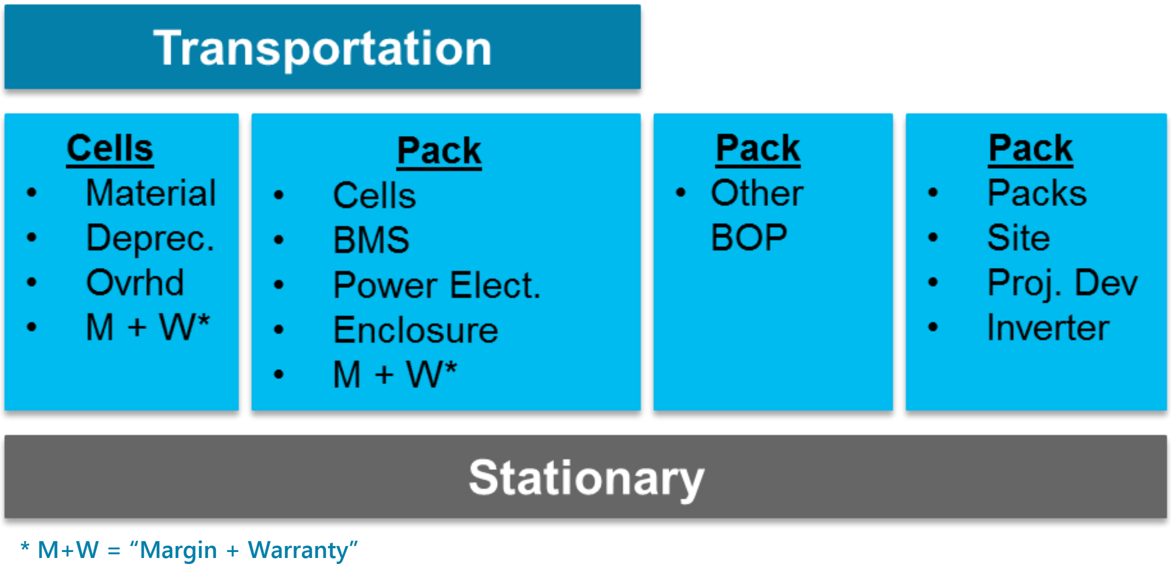


Figure 1: Levels of integration of battery system components into a full energy storage system

For the purposes of comparing different energy storage systems, we will use grid pack costs. As a baseline for comparison, we will often refer to recent advances in Li-ion batteries, where the most competitive transportation pack capital costs are reported to be about $300/kWh with the potential to drop below $200/kWh with scale up to production levels of 35 GWh per year. The round trip efficiency is reported as high as 92% with cycle life of 500-1000. Today's costs for stationary storage based on Li-ion batteries are reported to be a higher, at about $430/kWh for a grid pack suitable for daily cycling applications with ~3500 cycles, $500-700/kWh for energy applications and $1500-1700/kWh for power applications. If and when cycle life values reach 7000 cycles (so far demonstrated for the most expensive cells with lithium iron phosphate cathode), these costs would translate to costs per storage cycle of $0.080-0.11/kWh for energy applications and $0.24-0.27/kWh power applications (using Equation 1 and assuming a 90% round trip efficiency).

[41] Lazard's levelized cost of storage analysis – version 1.0. 2015 (https://www.lazard.com/media/2391/lazards-levelized-cost-of-storage-analysis-10.pdf)

II. Innovation in Batteries for Grid Storage

Building on early support from the DOE Office of Electricity[42], research and development into a variety of advanced types of battery storage technologies for grid applications has accelerated rapidly in the last decade. The aggressive technical and cost goals set by the GRIDS program in 2010 have helped define the technical challenges that must be addressed.

There are many types of approaches possible for lowering the cost of a grid-scale battery. These address different sources of cost for a battery system, which include the materials (in particular the active chemicals, electrode materials, and the electrolyte), the structural components (including separators and current collectors), the enclosure, and the battery management system. Unlike batteries for electric vehicles, where size and weight constrain possible solutions, approaches to battery development for the grid can address the cost drivers in a variety of ways. As described below, these include working with low cost and environmentally friendly battery chemicals, or with chemical couples of high theoretical specific energy (materials approaches) and/or making significant changes in the architecture of the battery itself (design approaches). Innovative uses of all of these approaches are represented in ARPA-E's grid-battery portfolio (Table 2).

Materials Approaches: When a battery can be designed to realize the potential of chemical couples with a high theoretical specific energy, the size (and consequently the cost) of the other components of the battery can be kept small. However, many known high-energy couples, e.g. lithium-sulfur, have presented serious difficulties in implementation, in particular those using metal anodes, due to dendrite formation. These problems can cause the battery to have a poor lifetime (capacity fade or battery short), or poor utilization of the energy that is theoretically available. On the other hand, the use of chemical couples based on very low-cost materials, even though they may have lower theoretical energy density, can provide a path toward very low-cost needed for grid storage. In addition, materials choices that are safer or more environmentally benign can allow lower-cost packaging and protection choices. Materials such as iron, zinc, and organic redox materials are significantly less expensive than proven high energy density materials such as lithium, nickel, and cobalt. Historically, attempts to develop battery systems using such materials have suffered a variety of materials and chemical problems.

Better understanding of chemistries of low-cost energy storage materials and the improved ability to diagnose the physical and chemical processes of the batteries have stimulated innovations in development of such systems. *ARPA-E projects developing batteries based on high-energy or low-cost materials include Fluidic (Zn-air); Primus (Zn-Br), PolyPlus (Li-sulfur); MIT (liquid electrode); Iowa State (Sodium) (high-energy); CUNY/UEP (Zn-manganese oxide); General Atomics (All-lead flow); UTRC/Vionx (Vanadium redox flow); USC (Iron-air); Alveo (organo-metallic); Sharp Labs (Sodium-organometallic); CWRU (Iron slurry flow); Harvard and USC (organic redox flow); ESS (Iron flow); USC (Iron-air) (low-cost materials)*.

Design Approaches: Batteries with liquid electrodes and redox flow batteries (RFB) represent major alternatives to standard battery designs, and are promising approaches for grid storage, as they have long battery life and, for RFB, the unique attribute of allowing for power and energy capacities to be independently managed[43]. RFBs store energy in liquid electrolytes that are pumped from storage tanks through a cell stack (the part of the battery where power is accepted or produced, including the electrodes) during charging and discharging, as illustrated in Figure 2. Historically, flow cells have been limited in delivering power because of high electrode resistance, poor kinetics, and ineffective flow fields. In addition, crossover of active materials through a separator has limited the cycle life of flow batteries. Improved

[42] http://energy.gov/oe/services/technology-development/energy-storage

[43] Yang, Z. et al., *Electrochemical Energy Storage for Green Grid*, Chem. Rev., 2011, *a11* (5), 3577–3613

understanding of fluid dynamics and advanced materials approaches to design of electrodes and electrolytes has provided new opportunities to dramatically increase the performance of flow batteries, as well as bring down their cost.

ARPA-E projects developing batteries with liquid electrodes and improved cell design include: *Ambri (all liquid-metal); EaglePicher (Sodium), Materials & Systems Research (Sodium) (liquid electrodes); MIT (liquid electrode); CUNY/UEP (Zn-manganese oxide); General Atomics (All-lead flow); LBNL and TVN (H2/Br), Primus (Zn-Br), UTRC/Vionx (Vanadium redox flow); PolyPlus (Li-sulfur); ITN (Vanadium redox flow); ESS (Iron flow); CWRU (Iron slurry flow); Teledyne (K-ion); U. Delaware (Zn-Ce); USC and Harvard (organic redox flow), 24M(slurry flow); USC (Iron-air) (low-cost materials).*

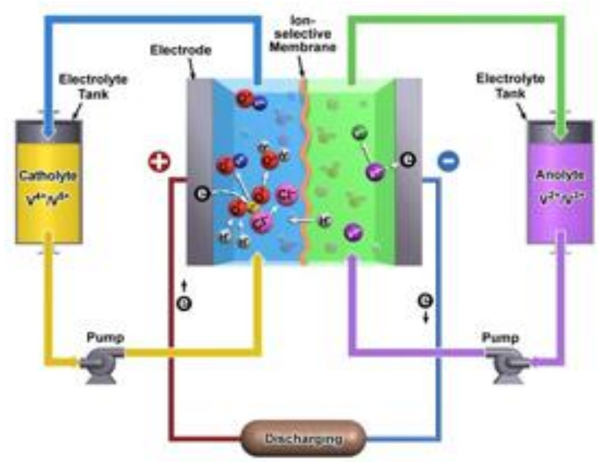


Figure 2: All Vanadium Redox Flow Battery (VRB)

Source: Yang, Z. et al., Electrochemical Energy Storage for Green Grid, Chem. Rev., 2011, 111 (5), 3577–3613

Table 2: ARPA-E Stationary Electrochemical Storage Portfolio

Organization/ *Battery Type*	**Concept**	**ARPA-E Program *(Project Term)***	**Cost Lowering Approaches**	
			Materials	**Design**
24M Technologies*/ *Flow*	Semi-solid flow cells for grid-level energy storage	BEEST *(9/01/2010 to 2/28/2014)*		X (and manufacturing)
City University of New York/ *Flow*	Flow-assisted rechargeable zinc-manganese dioxide battery	GRIDS *(9/15/2010 to 3/31/2015)*	X	X
Arizona State & Fluidic Energy/ *Metal-air*	Metal-air ionic liquid batteries & Advanced grid-interoperable power electronics enabling scalability and ultra-low cost	OPEN 2009 (12/21/2009-6/30/2012) & GRIDS *(10/1/2010 to 3/31/2013)*	X	
General Atomics/ *Flow*	Flow battery technology based on chemistry similar to that used in the traditional lead-acid battery	GRIDS *(9/1/2010 to 8/28/2013)*	X	X
Lawrence Berkeley National Laboratory/*Flow*	Hydrogen-bromine Flow Battery	GRIDS *(10/1/2010 to 9/30/2013)*		X
Primus Power/ *Flow*	Low-cost, high-performance 50-year electrodes for a zinc-bromine flow battery	GRIDS *(9/1/2010 to 12/31/2012)*		X
United Technologies Research Center/ *Flow*	Transformative electrochemical flow storage system (TEFSS)	GRIDS *(9/9/2010 to 9/30/2013)*	X	X

Organization/ *Battery Type*	**Concept**	**ARPA-E Program *(Project Term)***	**Cost Lowering Approaches**	
			Materials	**Design**
University of Southern California/*Metal-air*	Iron-air rechargeable battery	GRIDS *(10/1/2010 to 9/30/2013)*	X	X
EaglePicher Technologies/ *Sodium*	Planar rather than conventional, tubular sodium-beta [alumina] battery	OPEN 2009 *(2/1/2010 to 2/19/2017)*		X
Massachusetts Institute of Technology/ *Liquid electrode*	All-liquid battery containing liquid metal electrodes and a molten salt electrolyte	OPEN 2009 *(1/15/2010 to 9/30/2013)*	X	X (and manufacturing)
Alveo Energy/*Low cost materials*	Open framework electrode using Prussian Blue dye as the active material	OPEN 2012 *(2/21/2013 to 3/31/2016)*	X	
Case Western Reserve University/ *Flow*	Water-based, all-iron slurry flow battery	OPEN 2012 *(1/1/2013 to 6/30/2016)*	X	X
Harvard University/*Flow*	Small organic molecule based flow battery for grid storage	OPEN 2012 *(2/1/2013 to 3/25/2017)*	X	
PolyPlus Battery Company/ *Lithium*	Water-based lithium-sulfur (Li-S) battery	OPEN 2012 *(2/6/2013 to 6/31/2016)*	X	X
Sharp Laboratories of America/ *Sodium*	Sodium-based battery with Prussian Blue-derived cathode and complete battery integration	OPEN 2012 *(3/28/2013 to 3/27/2016)*	X	
Teledyne Scientific & Imaging/ *Flow*	Potassium-ion flow battery	OPEN 2012 *(2/4/2013 to 1/31/2014)*	X	
University of Delaware/ *Flow*	Double-membrane, triple electrolyte flow batteries (e.g., zinc–cerium)	OPEN 2012 *(1/9/2013 to 12/31/2016)*		X
University of Southern California/ *Flow*	Metal-free organic redox flow battery	OPEN 2012 *(3/1/2013 to 5/31/2017)*	X	
Energy Storage Systems/ *Flow*	10kW/80kWh energy storage system based on all-iron hybrid flow battery	GRIDS/SBIR *(10/1/2012 to 8/30/2017)*	X	X
ITN Energy Systems/ *Flow*	Vanadium redox flow battery cost-competitive with more traditional lead-acid batteries	GRIDS/SBIR *(10/1/2012 to 6/30/2015)*		X
Materials & Systems Research/ *Sodium*	Solid-state electrolyte membrane structure for use in advanced sodium batteries	GRIDS/SBIR *(10/1/2012 to 9/30/2017)*	X	

Organization/ *Battery Type*	**Concept**	**ARPA-E Program *(Project Term)***	**Cost Lowering Approaches**	
			Materials	**Design**
TVN Systems/ *Flow*	Advanced hydrogen-bromine flow battery with new catalyst and membrane	GRIDS/SBIR *(10/1/2012 to 6/30/2015)*		X
Iowa State University/ *Sodium*	Low Cost, Safe, and Efficient All Solid State Sodium Batteries for Grid-scale Energy Storage and Other Applications	OPEN 2015**	X	

*24M proposed technology focuses on vehicular batteries initially when it applied for funding to the BEEST program but during the project pivoted toward first applications in grid storage.
**Project is expected to be officially launched in early spring 2016.

ARPA-E's battery storage project portfolio has reached sufficient maturity to demonstrate both technological and commercial accomplishments. These include the formation of new start-up companies, follow-on funding for further development and demonstration, and commercial battery products that are currently being sold and deployed around the world, as summarized in the textbox below.

Follow-on Investments and Commercialization Highlights

- *At least 7 of ARPA-E's project teams working on stationary storage have raised more than $309 million in equity as well venture capital follow-on investments.*
- *One team has licensed its technology to a commercialization partner company*
- *2 companies have new commercial products on the market.*

III. Examples from ARPA-E's battery portfolio

Cost-Lowering Approach: Design

Primus Power: Low-Cost, High-Performance 50-Year Electrodes for a Zinc-Bromine Flow Battery (Hayward, CA; www.primuspower.com/index.html)

One of the most costly component in a flow battery is the electrode, where the electrochemical reactions actually occur. Primus focused on the development of a long-life electrode that successfully extends the stack lifetime and reduces system cost. The Primus team replaced the standard carbon-base for the electrodes with a new structure based on a metal substrate and structured mixed-metal catalyst, thus improving resiliency and electrical conductivity, and enhancing the surface area to support the catalysts that interact with the electrolyte. Primus ultimately developed a highly durable advanced metal electrode that significantly extends the stack lifetime.

Under its ARPA-E award, Primus' resulting system delivered 5X higher stack power than previous commercial Zn-Br batteries and cycle life that was 8X longer. Additionally, the lifetime of the Primus system substantially exceeded state-of-the-art cycles of 2,000 cycles over a typical stack lifetime, with higher than 17,000 cycles possible if degradation of components (including electrodes) is controlled.

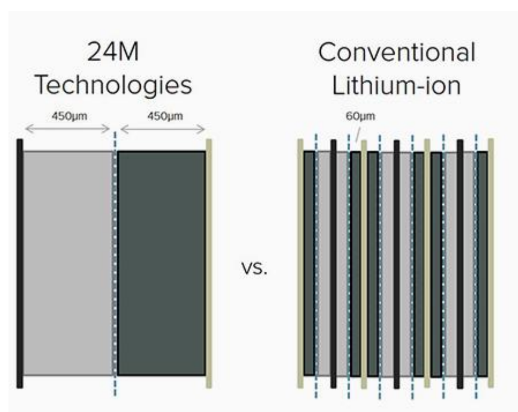
Primus Power has recently reported significant progress in commercialization of the products that resulted from Primus' ARPA-E research project. Primus Power has flow batteries available commercially in a modular 25kW • 125kWh system. It is developing market acceptance for its products through participation in demonstration projects, and has begun product sales.

A Primus battery is an integral part of a micro-grid (integrated with a 230kW solar photovoltaic array) being tested at the Marine Corps Air Station (MCAS) in Miramar, California. Primus has delivered ~20 battery systems and in September 2015 announced an order for 1,250 batteries from a major Asian utility with 21,000 MW of generating capacity. In October 2015, Primus delivered a "behind the meter" system to the ICL minerals manufacturing facility in Southern California. In early 2016, Primus shipped its first international system to Samruk-Energy, the principal electricity provider in the Republic of Kazakhstan.

Primus Power's flow battery system has demonstrated potential to deliver very long lifetimes, and to cost less when manufactured in high volumes than the projections for lithium ion batteries at scale.

24M Technologies: Semi-Solid Flow Cells for Grid-Level Energy Storage (Cambridge, MA; www.24-m.com)

The 24M team proposed to develop a low-cost, high energy density battery for electric vehicles using a new cell design. The team initially investigated a flow battery approach with conventional lithium-ion (Li-ion) active materials suspended in a slurry (semi-solid mixture). However, within the first year of the project, the 24M team determined that the flowing slurry concept was not commercially viable and transitioned to thick electrodes. This allowed them to re-evaluate the need for a flow-cell design for their batteries.



The slurry allows the delivery of the active Li material in the form of a film of closely packed particles in the form of a semi-solid flow, which greatly simplifies the battery design, as shown in the Figure to the right. The material delivered covers the current collector completely, and allows thicker films without the cracking and poor adhesion of traditional manufacturing processes. The new cells have an additional advantage of higher energy density than state-of-the-art large format Li-ion cells because they allow a larger ratio of active material to inactive material.

The 24M team demonstrated a low-cost, scalable fabrication process. The team concluded their ARPA-E project with the successful delivery of a 17Wh cell that used thick electrodes (>400 μm) with high loading of active materials (>40% vol), cycled at high efficiency (>85% roundtrip), and showed reasonable cycle life (>1000 cycles) with limited capacity loss. 24M designed the cell to operate at a continuous charge/discharge rate of C/4, and have also shown good performance in grid duty cycles with sustained power pulses of up to 2C.

Since the conclusion of its ARPA-E project, 24M has continued development of its technology and reported significant progress in commercializing the products that resulted from Primus' ARPA-E research project:

The research team has developed an automated cell fabrication process, and continued to enhance the performance of its cells, including extending cycle life and increasing active material loading. By driving down costs and improving performance, 24M's new cell promises to be very competitive compared with the incumbent Li-ion technology and its projected improvements. The batteries are targeted to providing grid services with intermediate power and energy requirements (~4 hour duration), such as peaker replacement systems, grid asset optimization, and renewable energy time shift. The company is developing strategic partnerships aiming to bring their product into volume production by 2018.

Cost-Lowering Approach: Materials

Arizona State University; Fluidic Energy: Metal-Air Ionic Liquid Batteries; Advanced Grid-Interoperable Power Electronics Enabling Scalability and Ultra-Low Cost (two related projects) (Tempe & Scottsdale, AZ; www.fluidicenergy.com)

One major issue for metal-air batteries is that the circulating air carries away evaporating liquids from the electrolyte, degrading battery performance over time. Another issue for the desirable, low-cost Zinc-air (Zn-air) battery is that zinc dendrites form on the anode as the battery is recharged, causing shorting. As a result, commercial Zn-air batteries historically had been limited to disposable (non-rechargeable), low power applications, such as hearing-aid batteries. Advances in materials science offered new opportunities to enable recharging and long lifetime operation.

With ARPA-E's support, Arizona State University, in partnership with Fluidic Energy, explored innovative approaches to transition nonrechargeable Zn-air battery chemisty into a rechargeable device. They focused on developing a battery design using an electrolyte based on ionic liquids. The team developed robust chemistries and include additives that interact favorably with the Zn and air electrodes. In parallel they experimented with carbon-nano-particle based air electrodes and nanostructured Zn electrodes, the latter including 3-dimensional porous structures that address the problems of Zn dendrites formation.

With ARPA-E's support, Fluidic Energy developed a commercial battery module, including the preliminary development of an advanced control system and integration of continuing improvements in the system of electrodes and electrolyte. Their system targets kW-level power applications with delivery over 4 to 72 hours, requiring cost and performance competitiveness with traditional back-up power based on diesel generators and/or lead-acid batteries.

Fluidic has reported the significant commercial developments, based on the results of its ARPA-E-funded research projects in its Zn-air battery and associated control system routines.

Fluidic has established its first markets in cell phone tower backup systems for developing regions, where reliable power delivery is essential. Fluidic's integrated smart controls, which provide remote monitoring, control and diagnostics of the complete energy storage system, have been important to successful commercialization in markets outside of the U.S. The company is now working to transition their technology to broader rural electrification and micro-grid applications. As of January 2016, Fluidic has installed more than 50,000 Zn-air battery cells, primarily in South East Asia and Latin America, reducing customer's operating costs while increasing reliability. As of January 2016, Fluidic also reports that the company is entering the rural electrification market, having been selected for 500-islanded renewable micro-grids by the Indonesian government.

In Fluidics' first applications, long-duration energy storage systems demonstrate the use of grid-scale storage for replacement of diesel generators, along with the associated CO2 emissions. As an ancillary benefit, many tons of ionic liquids—chemistries developed under the ARPA-E programs—have been manufactured and deployed by Fluidic Energy; this may be the largest commercial deployment of ionic liquids in the world, and may provide a basis for other commercial developments based on these materials.

Cost-Lowering Approaches: Design & Materials

United Technologies Research Center (UTRC): Transformative Electrochemical Flow Storage System (TEFSS) (East Hartford, CT; www.utrc.utc.com)

United Technologies Research Center (UTRC) focused on designing a high-power cell that extracted more power without increasing the scale of the expensive components, ultimately reducing the capital cost of the stack per watt of power generated.

UTRC's high-power flow battery, which delivered peak power of nearly 1400mW/cm2, a tenfold increase over state-of-the-art flow cells at the time, proved to be a key innovation. While UTRC's basic high-power cell design was developed utilizing all-vanadium systems, it can be applied in any flow battery system that uses liquid reactants and produces liquid reaction products.

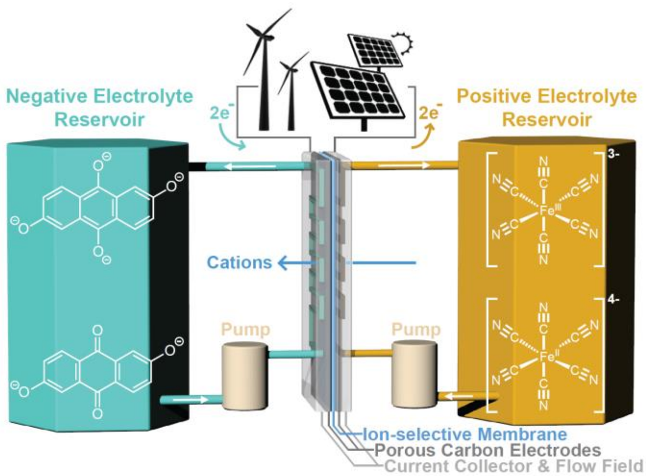
Following UTRC's successful increase in power density of the cell stack, UTRC addressed another key issue for stability and cost: membrane optimization. UTRC worked with 3M to fabricate a membrane that maintained high-proton conductivity but offered low permeability to vanadium. The resulting membrane permitted a doubling in operating current density of UTRC cells, further increasing stack power density and decreasing stack cost. UTRC's successful development of a high-power stack enabled a > 2X reduction in cost (which makes it competitive with today's lithium-ion-based storage systems) while also offering a lifetime of > 7,500 cycles.

As of November 2015, UTRC licensed its high-power all-vanadium system to Vionx Energy. The company has containerized 65kW/400kWh energy storage units for sale. Vionx deployed its first unit to the U.S. Army at Fort Devens, Massachusetts in 2015. Vionx is collecting data based on 160kW to 500kW systems in the field and will use this data to determine future market opportunities.

UTRC's development of a high-power all-vanadium battery is a significant demonstration in the ability to advance energy storage to the lower costs and higher performance needed both for first market applications in micro-grids, and for longer term, larger scale applications.

Harvard University: Small Organic Molecule Based Flow Battery for Grid Storage (Cambridge, MA; www.seas.harvard.edu/news-events/press-releases/greener-storage-for-green-energy)

The Harvard team is addressing the challenges of grid storage by designing a flow battery based on inexpensive organic molecules in aqueous (water-based) electrolyte. The team has focused on non-toxic quinone molecules, which can be found in plants such as rhubarb, as an electroactive chemical that can reversibly store energy in a water-based solution at room temperature. The group employed theoretical and organic synthetic methods to evaluate hundreds of thousands of possible quinone-based chemicals that might offer the necessary electrochemical potential, solubility in water, and thermodynamic stability.



The first demonstration of these systems, 2,7-anthraquinone disulfonic acid coupled to a bromine solution, has a reduction-oxidation window of 0.8 V. Details of this early, proof of concept battery were published in 2014[44].

Since these experiments were completed, the group has moved to make their system cheaper and less toxic, and to increase the voltage to 1.2 V. The team has developed a prototype cell design using safer alkaline liquids, no precious metals, and other battery components made of plastic or inexpensive metals with coatings proven to protect against corrosion. The relatively non-toxic chemicals used in the battery design are widely used in the textile dye industry. Because these materials are already in commercial production, it is likely that scale-up for the organic battery will be rapid and cost effective. Their goal is to have a pilot-sale system ready for external testing by the end of the performance period.

Sustainable Innovations, Harvard's commercialization partner, is developing a 3kW system incorporating Harvard's chemistry for demonstration by the end of the performance period. If Harvard's innovative storage concept proves commercially competitive, this technology can be inserted into a low-cost platform to yield a range of quinone based battery systems, with toxicity, cost and performance features that suit a variety of applications ranging from uninterruptable power supplies through micro-grid back-up, to full grid support.

The use of redox-active organics in flow batteries has the potential to significantly drop the cost and toxicity of large-scale grid storage batteries. With continuing development, and scale up to manufacturing in large quantities, redox-active organic battery technology has the potential for a highly competitive evolution of costs.

Energy Storage Systems (ESS): 10kW/80kWh Energy Storage System Based on All-Iron Hybrid Flow Battery (Portland, OR; www.energystoragesystems.com)

Energy Storage Systems (ESS) initially focused on developing a high-power cell and a compact stack design based on vanadium chemistry. ESS then evaluated other chemistries to address the high cost of the vanadium-carrying electrolytes, which was a large fraction of overall system cost. Early academic literature on the iron-flow battery (IFB) indicated a potential low-cost approach using abundant iron as the active material, but state-of-the-art power densities were low (50mW/cm2), so there was a clear opportunity to leverage ESS' high-power cell design in conjunction with the iron chemistry.

ESS adapted its cell and stack design to use iron chloride (FeCl2) electrolytes that cost less than 1/10 of the vanadium-carrying electrolytes. The resulting high-power cell design has demonstrated a four-fold power density increase over existing iron flow battery technologies.

When ESS began its project, state-of-the-art IFBs exhibited round trip efficiency of roughly 50% and life of less than 100 cycles. Chemical side reactions limited the cycle life by altering the pH of the electrolyte and causing precipitation of active species. The ESS team developed an effective chemical rebalancing system that ensures the IFB can cycle over extended periods. After incorporation of its rebalancing system, ESS demonstrated single-cell cycle life of >2500 cycles without measurable degradation, and AC energy efficiency of 70% in a scaled-up 10kW/75kWh IFB.

ESS' first markets for the product are customer-owned systems (<100kW in size) coupled with renewables for firming and load management. To increase customer benefits, ESS has developed a battery management system in which end-users have a way to harness their local electricity rates structures to their economic advantage. ESS' first customers include the U.S. Army Corps of Engineers and Stone Edge Farms, a winery in Napa, CA. In addition, ESS has

[44] B. Huskinson, M.P. Marshak, C. Suh, S. Er, M.R. Gerhardt, C.J. Galvin, X. Chen, A. Aspuru-Guzik, R.G. Gordon and M.J. Aziz, "A metal-free organic-inorganic aqueous flow battery", *Nature* **505**, 195 (2014).

approximately $1 million in firm orders for delivery in the first half of 2016. As ESS moves into higher-volume production, the company is also seeking to drive cost out of its system through manufacturing improvements.

The successful application of high-power flow-cell designs, and the development of approaches to address chemical imbalances and incorporate lower-cost materials remove the two most serious barriers to commercial applications of flow batteries for grid storage. ESS' results help to position flow cells to move into the larger applications in the grid needed to create significantly expanded integration of intermittent renewable power sources.

IV. Potential Impacts for the Energy Sector

Since 2009, ARPA-E has maintained a focus on the challenge of developing cost-competitive energy stationary storage technology, funding over $85 million in research and development of potentially transformative approaches. The most successful of the resulting battery technologies have the potential for very low capital cost (<$100/kWh at the pack level for batteries), with performance characteristics suitable for a range of grid services, including leveling variability in capacity.

As reviewed in Appendix B, stationary energy storage provides a significant option for improving the electric power grid and enabling the integration of larger amounts of intermittent renewable energy[45]. It is reasonable to assume that the amount of storage needed, of all forms, may be on the scale of 100s of GW in the U.S. alone. This requires production and implementation of stationary storage devices to grow rapidly from the present installed systems base of hundreds of MW for batteries, and overall storage capacity of about 25 GW.

A recent announcement by electric vehicle manufacturer, Tesla Motors, of its plans to produce Li-ion battery packages for residential, commercial, and utility customers has set a competitive baseline for the present market for back-up power and grid services. Tesla's plans to ramp up production to a scale of 35 GWh per year sets the potential to drive cost down the learning curve, with a potential of dropping well below pack costs of $300/kWh for grid applications. At a 90% round trip efficiency and potential cycle life of 5000, this would correspond to a package cost of storage[46] less than $0.07/kWhe (not including installation and air conditioning costs).

The new battery chemistries and designs in ARPA-E's portfolio have demonstrated the potential for ultimately achieving lower costs than the limiting values possible for the mature Li-ion technology that Tesla motors is now using. For instance, the new manufacturing approach and battery design developed by 24M for Li-ion batteries has the potential to drive the pack cost below $100/kWh. The advances in flow battery design pioneered by UTRC/Vionx make the vanadium-based flow competitive at scale with the mature Li-ion technology. When coupled with very low-cost materials and designs that stabilize electrolytes and electrodes, flow cells such as those of ESS and Primus can achieve both lower cost and longer cycle life, offering the potential for pack-level cost of storage below $0.02/kWhe, which would be transformative. Ambri's liquid metal battery provides another approach with low-cost materials and long lifetime, and Harvard's and USC's batteries based on low-cost organic and organo-metallic offer lower balance of system costs due to lower toxicity and reduced safety issues.

Developing first markets, and demonstrating value delivery in applications, as Fluidic Energy has done with its Zn-air battery and service model, is essential to continuing development of every new storage technology[47]. Commercial penetration will occur first in the U.S. where there are policy drivers (as in California), special performance needs (as for

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[45] Additional options include improved efficiency to reduce overall demand, increasingly sophisticated demand management, optimization of transmission and distribution protocols, power flow control, use of gas peakers coupled with carbon capture and storage, or, simply, even greater over-build of capacity. Some combination of these options with physical storage is likely to be required.

[46] As defined in Section I, Eq. 1.

[47] ARPA-E's CHARGES program is providing rigorous testing opportunities for performers to demonstrate battery performance under grid conditions with high renewables penetration.

some back-up power and micro-grid applications), or the potential to develop immediate economic gains (as in market arbitrage). Large-scale penetration will need to demonstrate a cost structure competitive with alternatives such as using gas peaking-power to address variations in demand. A storage cost below $0.02 could make that possible.

The two project teams in the ARPA-E CHARGES program are working now to quantify the value of the grid storage batteries, develop realistic duty cycles for storage devices on a micro-grid, and test emerging battery storage systems in both a controlled environment and under realistic micro-grid operating conditions. This program aims to accelerate the commercialization of electrochemical energy storage systems developed in current and past ARPA-E-funded research efforts by giving those battery development teams a clear understanding of value-driven performance requirements that allow for evaluation of their technology early in the development cycle. The performance data that is generated will provide potential end-users of energy storage systems with validated information from a trusted third party about the performance and value of novel grid storage technologies that are currently in development.

ARPA-E's investment in novel grid storage battery approaches has significantly expanded the competitive space of technical approaches and introduced new potential to change the future of grid storage. We expect that over the next five to ten years, there will be a dynamic and competitive market that will build on the breadth of these options for value delivery in the context of the modernization of the electric power grid and integration of increasing levels of renewable power generation.

Given the enormous impacts of low-cost energy storage for deployment of renewable energy, and the significant technical opportunities still present, ARPA-E continues to invest in this space. The Integration and Optimization of Novel Ion-Conducting Solids (IONICS) program, released in 2016, seeks to significantly advance the properties of solid ion conductors needed to enable transformational, high energy density, and long cycle life electrochemical cells. This program seeks to create battery components built with solid ion conductors that have a wide range of desirable properties including low area-specific resistance, high chemical and electrochemical stability, high selectivity, good mechanical properties, and others, through innovative approaches to overcome tradeoffs among coupled properties. It also seeks to develop and apply transformative methods for solids processing and their integration into electrochemical devices. One of the categories of the IONICS program is specifically focused on batteries with liquid reactants (including flow batteries), and seeks the development of solid separators that will have high selectivity and be specifically designed to further improve performance of some of the new battery chemistries developed in previous ARPA-E programs. If successful, it will allow reducing the system cost by about $150/kW (or $30/kWh for a 5-h discharge time) and advancing their deployment and the impacts that come with low-cost energy storage.

APPENDIX A: ARPA-E's Energy Storage Project Portfolio, Publications, and Patents

Since ARPA-E's launch, energy storage-related technology challenges took center stage of its emerging programmatic portfolio. Indeed, two of the first ARPA-E programs, launched in 2010, focused on specific solutions to related technology challenges: the *Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)* and *Batteries for Electrical Energy Storage in Transportation (BEEST)*, which focused on electric grid and vehicular energy storage applications, respectively. In all, ARPA-E established 5 focused programs to provide innovative and potentially transformational energy storage-related solutions, in addition to several separate projects that were funded under ARPA-E's OPEN program solicitations in 2009, 2012, and most recently in 2015 (115 projects in total of which 79 were of the electrochemical types, as noted in Table A1)[48].

Table A1: ARPA-E's Energy Storage Project Portfolio*

Program (Launch Year)	Energy Storage Technology Area(s)	Number of Projects
OPEN (2009)	Transportation & Stationary: metal-air; flow cells, capacitors, solid state	7
BEEST (2010)	Transportation: high energy density	10
GRIDS (2010)	Stationary: flow cells, conventional cells, SMES, reversible fuel cell, flywheels	13
HEATS (2011)	Transportation & Stationary: thermal storage technologies	15
OPEN (2012)	Transportation & Stationary: new flow cell chemistries; solid state	19
AMPED (2012)	Transportation & Stationary: improved battery management system algorithms and sensors	14
SBIR (2012)**	Transportation & Stationary: flow cells, advanced membranes, high-temp cells	7
RANGE (2013)	Transportation: Robust lower energy density incorporated into vehicle design	22
CHARGES (2014)	Stationary: controlled and realistic testing of grid storage technologies	2
OPEN (2015)***	Transportation & Stationary: solid state, chemical storage, enabling technologies (e.g., flow cell membranes)	6

* The vast majority of the projects (79 projects) were of the electrochemical storage type.

** SBIR = Small Business Innovation Research.

More information on listed programs and projects is available on ARPA-E's website: http://arpa-e.energy.gov/?q=projects/search-projects."

*** Projects are expected to be officially launched in the spring 2016 timeframe.

[48] As noted earlier, most recently, ARPA-E announced the selection of 4 new grid-scale storage projects through the OPEN 2015 funding opportunity announcement. A description of these is available at http://arpa-e.energy.gov/sites/default/files/documents/files/OPEN_2015_Project_Descriptions.pdf. These projects are currently being negotiated for final awards.

CHANGING WHAT'S POSSIBLE

Table A2: Example Publications for Stationary Battery Storage Technologies Funded by ARPA-E

Team	Authors	Title	Journal Title (Year)	Doi
City University of New York	Gallaway, JW; Sviridov, LA; Sholklapper, TZ; Turney, DE; Banerjee, S	Real-time materials evolution visualized within intact cycling alkaline batteries	Journal of Materials Chemistry A (2014)	10.1039/c3ta15169g
Lawrence Berkley National Lab	Cho, KT; Ridgway, P; Weber, AZ; Haussener, S; Battaglia, V; Srinivasan, V	High Performance Hydrogen/Bromine Redox Flow Battery for Grid-Scale Energy Storage	Journal of the Electrochemical Society (2012)	10.1149/2.018211jes
University of Southern California	Malkhandi, S; Trinh, P; Manohar, AK; Jayachandrababu, KC; Kindler, A; Prakash, GKS; Narayanan, SR	Electrocatalytic Activity of Transition Metal Oxide-Carbon Composites for Oxygen Reduction in Alkaline Batteries and Fuel Cells	Journal of the Electrochemical Society (2013)	10.1149/2.109308jes
University of Southern California	Malkhandi, S; Yang, B; Manohar, AK; Manivannan, A; Prakash, GKS; Narayanan, SR	Electrocatalytic Properties of Nanocrystalline Calcium-Doped Lanthanum Cobalt Oxide for Bifunctional Oxygen Electrodes	Journal of Physical Chemistry Letters (2012)	10.1021/jz300181a
University of Southern California	Manohar, AK; Malkhandi, S; Yang, B; Yang, C; Prakash, GKS; Narayanan, SR	A High-Performance Rechargeable Iron Electrode for Large-Scale Battery-Based Energy Storage	Journal of the Electrochemical Society (2012)	10.1149/2.034208jes
United Technologies Research Center	Darling, RM; Perry, ML	The Influence of Electrode and Channel Configurations on Flow Battery Performance	Journal of the Electrochemical Society (2014)	10.1149/2.0941409jes
Harvard University	Huskinson, B; Marshak, MP; Suh, C; Er, S; Gerhardt, MR; Galvin, CJ; Chen, X; Aspuru-Guzik, A; Gordon, RG; Aziz, MJ	A metal-free organic–inorganic aqueous flow battery	Nature (2014)	10.1038/nature12909
Harvard University	Lin, K., Q. Chen, M. R. Gerhardt, L. Tong, S. B. Kim, L. Eisenach, A. W. Valle, et al.	Alkaline quinone flow battery	Science (2015)	10.1126/science.aab3033

Table A3: Published U.S. Patents for Stationary Battery Storage Technologies Funded by ARPA-E (as of February 2016)*

Team	Patent Title	U.S. Patent Number	Issue Date
24M Technologies	Semi-Solid Electrodes Having High Rate Capability	8,993,159	3/31/2015
24M Technologies	Electrochemical Cells and Methods of Manufacturing the Same	9,178,200	11/3/2015
24M Technologies	Semi-Solid Electrodes Having High Rate Capability	9,184,464	11/10/2015
24M Technologies	Stationary Semi-Solid Battery Module and Method of Manufacture	9,203,092	12/1/2015
Massachusetts Institute of Technology	Alkali-Ion Battery with Bi-Metallic Cathode	9,000,713	4/7/2015
Massachusetts Institute of Technology	High Temperature Sealed Electrochemical Cell	9,153,803	10/6/2015
Alveo Energy	Homometallic cyanide-containing inorganic polymers and related compounds	9,099,740	8/4/2015
Alveo Energy	Stabilization of battery electrodes	9,130,234	9/8/2015
Alveo Energy	Stabilization of battery electrodes using prussian blue analogue coatings	9,123,966	9/1/2015
Sharp Laboratories of America	Hexacyanoferrate Battery Electrode Modified with Ferrocyanides or Ferricyanides	9,099,719	8/4/2015
Sharp Laboratories of America	Metal-Doped Transition Metal Hexacyanoferrate (TMHCF) Battery Electrode	8,968,925	3/3/2015
Sharp Laboratories of America	Transition metal hexacyanometallate-conductive polymer composite	9,083,041	7/14/2015
Arizona State University	Metal-Air Low Temperature Ionic Liquid Cell	8,895,197	11/25/2014
Arizona State University	Metal-Air Cell with Performance Enhancing Additive	9,184,478	11/10/2015
Arizona State University	Aluminum-Based Metal-Air Batteries	9,236,643	1/12/2016
Fluidic, Inc.	Metal-Air Cell Comprising an Electrolyte with a Room Temperature Ionic Liquid and Hygroscopic Additive	8,808,929	8/19/2014
Fluidic, Inc.	Degenerate Doping of Metallic Anodes	9,029,027	5/12/2015
Fluidic, Inc.	Ionic Liquid Containing Sulfonate Ions	8,741,491	6/3/2014
Fluidic, Inc.	Metal-Air Cell with Ion Exchange Material	9,118,089	8/25/2015

Team	Patent Title	U.S. Patent Number	Issue Date
Fluidic, Inc.	Methods of Producing Sulfate Salts of Cations from Heteroatomic Compounds and Dialkyl Sulfates and Uses thereof	9,147,919	9/29/2015
Primus Energy	Electrolyte Flow Configuration for a Metal Halogen Flow Battery	8,137,831	3/20/2012

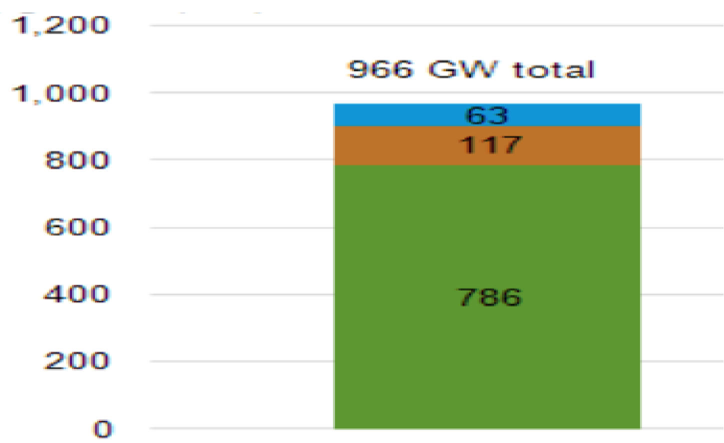
* In addition to the patents listed here, there have been 127 invention disclosures and 72 patent applications, some of which may lead to additional patents.

APPENDIX B: BACKGROUND: ENERGY STORAGE NEEDS AND APPROACHES

Stationary Energy Storage: What is it and why is it needed?

The current U.S. electrical power grid was designed for centralized production of base-load power generation, primarily from thermoelectric plants burning fossil fuels, which still account for about 2/3 of our electricity generation. Variability in demand and supply has been met by grid operations based on significant over-capacity. As shown in Figure B1, the grid capacity is maintained 15-20% higher than the expected annual peak demand, and that results in overall capacity that is about two times larger than the actual amount of electricity that is actually consumed annually.

Figure B1: Annual peak demand (green), target reserves (brown) and additional capacity (blue) in gigawatts (GW) for 2013*



*Actual total US consumption of electrical power was 464 GW in 2013.

Source: U.S. Energy Information Administration (EIA) and North American Electric Reliability Corporation, 2012 Long-Term Reliability Assessment, and EIA Electricity Data Browser (http://www.eia.gov/electricity/data/browser).

The multiple drivers for grid modernization, including growing use of distributed generation and intermittent renewable sources, require improved methods of managing variability, both regional and temporal, of supply and demand. Energy storage provides one significant option for managing variability[49]. The amount of storage that will be needed is unclear, but it is reasonable to assume that it may be on the scale of 100 GW or more, based on Figure B1. Low-cost, high-performance and a rapid ramp-up in supply and implementation from today's levels, shown in Figure B2, will be needed meet the needs of a modernized grid[50].

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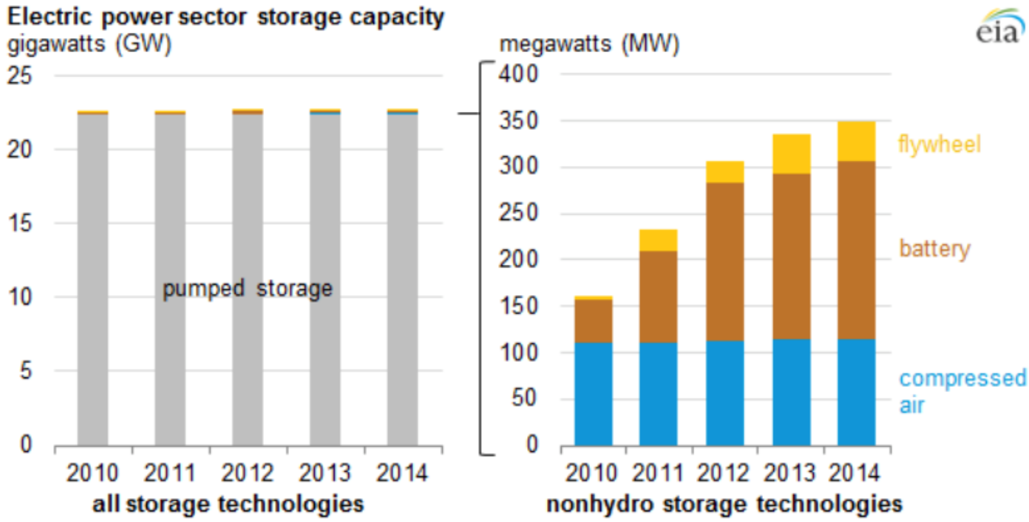
[49] Additional options include improved efficiency to reduce overall demand, increasingly sophisticated demand management, optimization of transmission and distribution protocols, power flow control, use of gas peakers coupled with carbon capture and storage or, simply, even greater over-build of capacity. Some combination of these options with physical storage is likely to be required.

[50] US DOE's grid storage strategy is outlined in the December 2013 publication Grid Storage, available at http://energy.gov/oe/downloads/grid-energy-storage-december-2013

Figure B2: U.S. Grid Storage Capacity



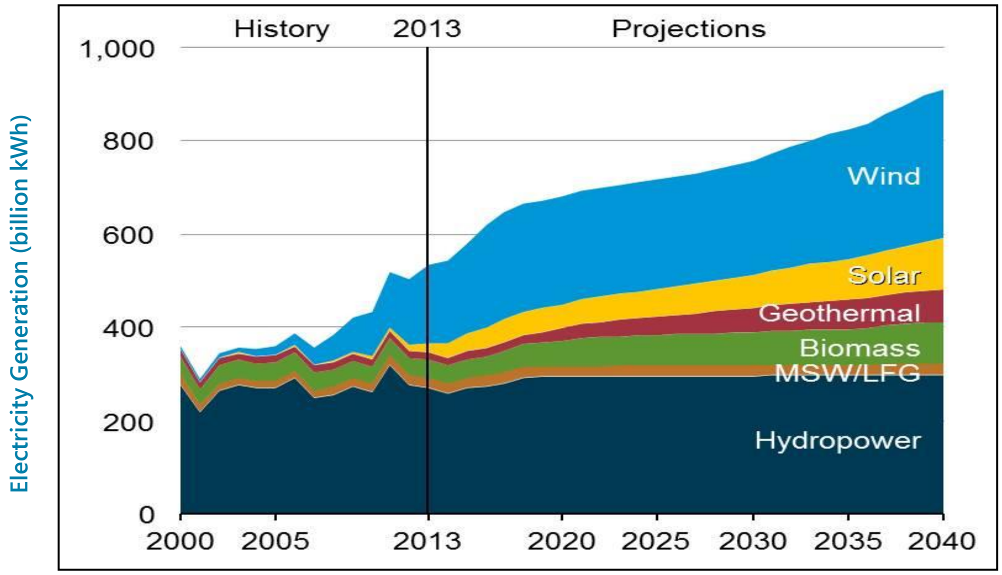
Source: U.S. Energy Information Administration, EIA-860 Survey; Sandia National Labs, DOE Global Energy Storage Database

The contribution of renewable energy to the overall electricity generation in the U.S. have been continuously increasing, due in part to the adoption of renewable portfolio standards (RPS) in many states and the precipitous drop in the cost of electricity generated from wind (wind mills) and solar (photovoltaic collectors) energy sources. RPS required electric utilities and other retail electric providers to supply a specified minimum percentage of customer demand with eligible sources of renewable energy. Today, 29 states and the District of Columbia have established mandatory RPS, with the large state of California implementing one of the most aggressive RPS goals of 33% electricity generation from renewable energy by 2020[51]. As a result, the U.S. electric grid is forecast to have increasing penetration of renewables over the next several decades, with wind and solar generation accounting for nearly two-thirds of the growth in renewable generation through 2040 (Figure B3).

The increased use of renewable energy lowers emissions of greenhouse gas (GHG) emissions, especially carbon dioxide; where they displace coal-fired generation, renewables also result in improved air quality. However, the growth in wind and solar electricity generation has also introduced significant challenges of intermittency and variability associated with solar and wind energy. These in turn can hinder their integration into the grid as a reliable source of electricity generation. Figure B4 illustrates examples of the strong variability of power output that occurs from solar and wind power sources on the minute to hour time scale, with intermittent power changes of over 80%.

[51] EPA Energy and Environment Guide to Action, Ch. 5 (2015).

Figure B3: Renewable Electricity Generation by Fuel Type in the EIA Reference Case (2000-2040)

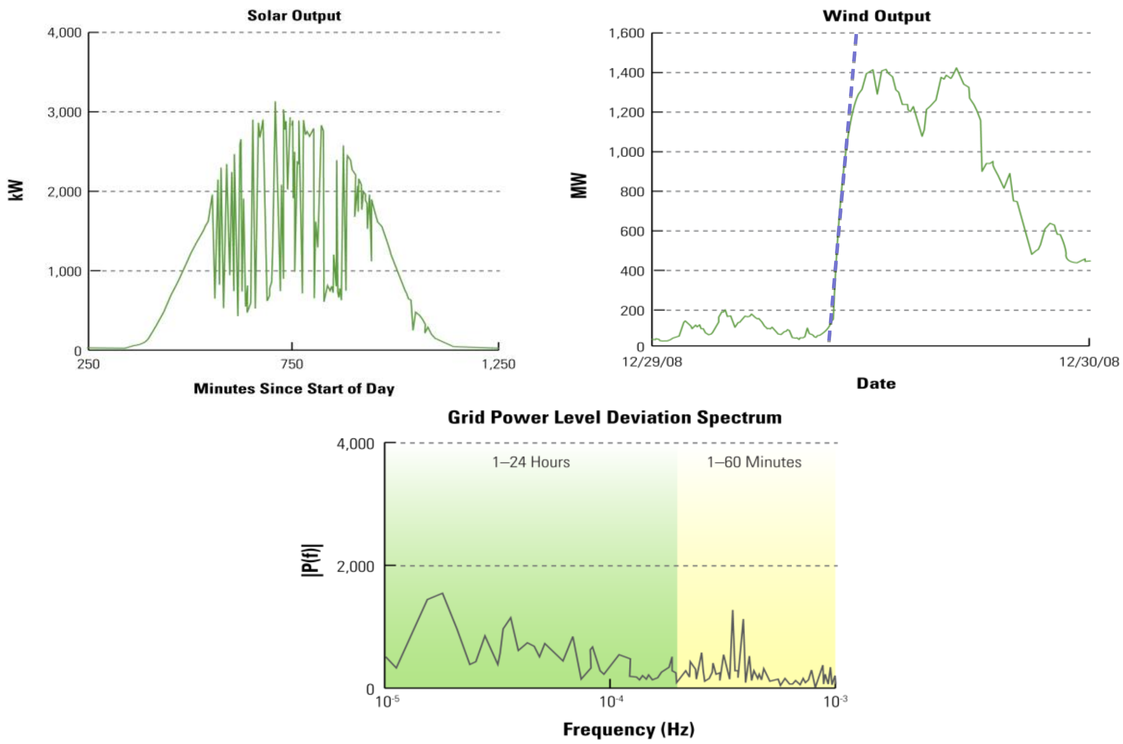


Source: U.S. Energy Information Administration (EIA) Annual Energy Outlook 2015
http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

The California Independent System Operator (ISO), like many other grid operators, uses the "Duck Curve" to illustrate the relationship of demand and supply of renewable electricity generation. During the early afternoon hours, when solar electric generation is a significant contributor to power production, the need for base-load generation can be significantly reduced. However, in the early evening hours, much of that solar production is gone, and demand has to be met quickly from other sources with the ability to ramp up production in as little as 3 hours (see Figure B5).

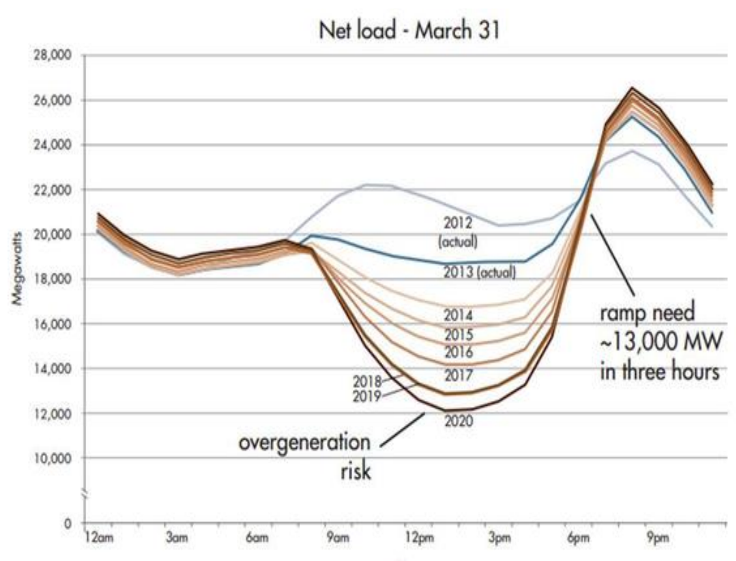
Energy storage technologies can be utilized to store energy during times of low demand and high production of electricity and then discharge it as electricity during peak demand times and when baseload electricity generation is insufficient to meet demand. As such, these devices can also help make renewable energy (for which power output cannot be controlled by grid operators) smooth and dispatchable. They can also balance micro-grids to achieve a good match between generation and load. Storage devices can provide frequency regulation to maintain the balance between the network's load and power generated in addition to providing a more reliable power supply for high-tech industrial facilities.

Figure B4: Intermittency in power generation within a day for (a) solar and (b) wind generation. A power spectrum (c) shows the frequency of grid deviation between generation and load in the minutes-to-hours and hours-to-days timeframe on the grid.



Source: ARPA-E Funding Opportunity Announcement (DE-FOA-0000290: GRID-SCALE RAMPABLE INTERMITTENT DISPATCHABLE STORAGE (GRIDS))

Figure B5: Historical and Projected Net Power Load for California. The vertical axis displays the difference between demand and the amount of electrical power delivered by wind and solar sources between 2012 and 2020 (projected).



Source: California ISO, July 2015

The main types of energy storage technologies deployed today are: pumped hydro, compressed air storage systems (CAES), thermal storage systems, electrochemical storage systems (mostly batteries), and flywheels (see Table B1 below). Currently, the U.S. has approximately 21.4 GW of operational grid storage capability[52] (or about 1.8% of total U.S. nameplate electricity generation capacity in 2013[53]), of which 95% is pumped hydro and the remaining 5% are the combined contribution of the other storage technologies (Table B1). Even though pumped hydro is the most common energy storage technology in the U.S. (and in the world), limiting siting requirements and initial high capital costs constrain the wider deployment of such systems.

Table B1: Storage Technologies and Respective U.S. Generation Capacity

Storage Technology	Description*	Current U.S. Nameplate Generation Capacity (MW)**
Pumped Hydro	Uses two water reservoirs, separated vertically. During off-peak hours, water is pumped from a lower reservoir to an upper reservoir. The operation is reversed to generate electricity via turbines.	20,356
Thermal	Thermal energy is stored in cold or hot storage reservoirs for later use. Types of storage include concentrating sunlight to produce electricity from solar thermal energy during non-solar periods and the production of ice, chilled water, or salt solution at night, or hot water, which the devices use to cool/heat environments during the day.	553
Compressed Air Energy Storage (CAES)	Off-peak energy is stored in the form of compressed air, typically in an underground reservoir. The air is heated with exhaust heat from a standard combustion turbine and released during peak load times. The heated air is converted into electricity using expansion turbines.	114
Electrochemical Storage* **	Batteries take in electricity from another producing source, convert the electricity to chemical energy, and store it in a liquid or solution. An electric charge chemically converts the energy back into electrons, which then move back into a power line on the electric grid.	372, of which: Li-ion = 238 Adv. PbA = 63 Ni = 27 NaS = 20 VBR (flow) = 2 Other = 22
Flywheels	A rotor (flywheel) is accelerated to a very high speed, maintaining the energy in the system as rotational energy. Energy is extracted from the system by reducing the flywheel's rotational speed as a consequence of the principle of conservation of energy. Adding energy to the system correspondingly results in an increase in flywheel speed.	56

* Adapted from "Andris Abele, Ethan Elkind, Jessica Intrator, Byron Washom, et al (University of California, Berkeley School of Law; University of California, Los Angeles; and University of California, San Diego) 2011, *2020 Strategic Analysis of Energy Storage in California*, California Energy Commission. Publication Number: CEC-500-2011-047."
** Operational. *Source: DOE Global Energy Storage Database, http://www.energystorageexchange.org/ (Dec 6, 2015).*
*** Electrochemical capacitors (ECs) are also of this type. ECs store direct electrical charge in the material, rather than converting the charge to another form, such as chemical energy in batteries. The devices may have longer useful lives since there is little breakdown in the capacitors ability to store energy electrostatically. Currently, electrochemical capacitors can store significantly more energy than dielectric and electrolytic capacitors; however, EC technology is still cost prohibitive (Grid Energy Storage, US DOE Report, 2013).

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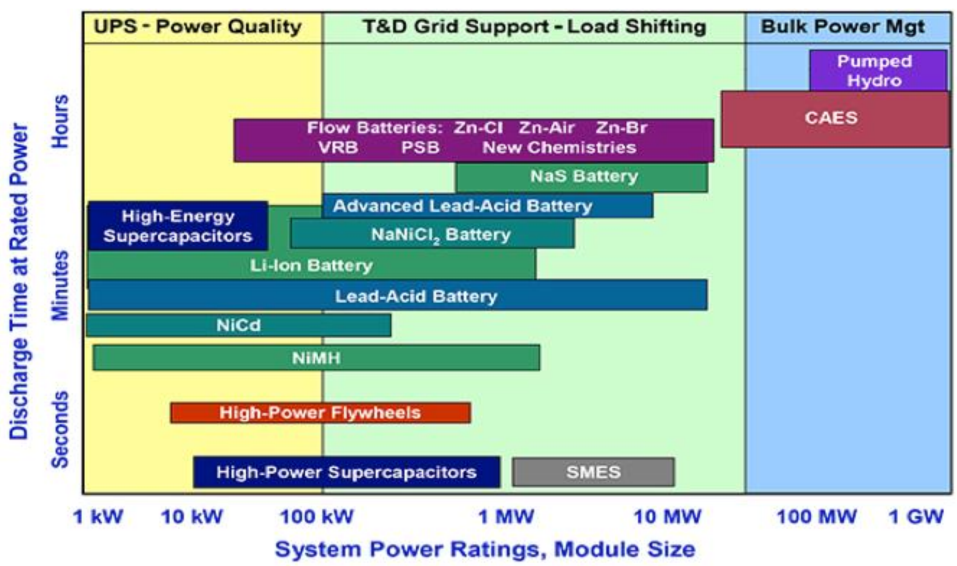
[52] The DOE Global Energy Storage Database, http://www.energystorageexchange.org/.

[53] EIA, Existing Capacity by Energy Source, 2013 (Megawatts), http://www.eia.gov/electricity/annual/html/epa_04_03.html.

Electrochemical storage systems—specifically *battery technologies*—provide diverse options for stationary storage applications, as illustrated in Figure E6. Table 1 in Section I further illustrates the wide-ranging applications of electrochemical storage solutions in providing a variety of grid services. These applications span timescales (from just minutes to several hours) and power requirements (from a few kilowatts to hundreds of megawatts). Indeed, according to a recent report the global energy storage business could grow from \$200 million in 2012 to a \$19 billion industry by 2017[54].

Figure B6: Stationary Energy Storage Options for the Grid: Electrochemical Storage Options offer a Wide Range of Applications



Source: DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECAS

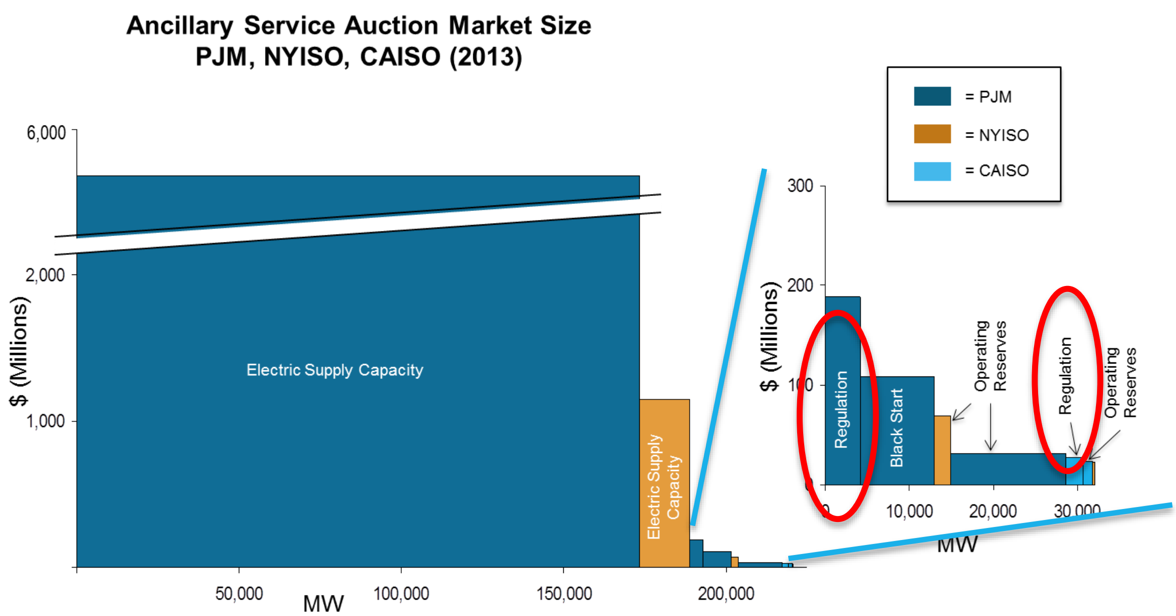
Notes: UPS = Uninterrupted Power Supply; T&D = Transmission and Distribution

[54] IMS Research (now owned by IHS-CERA) report 'The Role of Energy Storage in the PV Industry – World – 2013 Edition', cited in "Grid Energy Storage", a U.S. DOE Report, December 2013.

APPENDIX C: Market Size of Ancillary Grid Services

Although stationary battery storage solutions for grid-related frequency regulation is a high value service, the market for that type of service is much smaller than the potential deployment of battery storage systems for electric supply capacity, as illustrated in Figure C1.

Figure C1: Relative Sizes of the Grid Ancillary and Capacity Markets



Source: ISO/RTO Council; CAISO, NYISO and PJM State of Market Reports; CAISO, NYISO and PJM websites

FOR MORE INFORMATION

Additional Impact Sheets are expected to be ready in Fall 2016. This sheets will include:

- Dioxide Materials, Inc. (OPEN 2012) – Converting CO_2 into Fuel and Chemicals
- LanzaTech (REMOTE) – Bioreactor With Improved Methane Transfer
- Massachusetts Institute of Technology (Electrofuels) – Natural Oil Production From Microorganisms
- North Carolina State University (PETRO) – Jet Fuel From Camelina
- OPX Biotechnologies (Electrofuels) – Engineering Bacteria For Efficient Fuel Production
- Otherlab, Inc. (MOVE) – Safe, Dense, Conformal, Gas Intestine Storage
- Otherlab, Inc./Sunfolding (OPEN 2012) – Small Mirrors for Solar Power Tower Plants
- University of California Los Angeles (REMOTE) – High Efficiency Methanol Condensation Cycle
- University of California Berkeley (IMPACCT) – Metal Organic Framework Research
- University of California Berkeley (OPEN 2012) – Micro-Synchrophasors for Distribution Systems
- University of Texas Austin (OPEN 2012) – Low-Cost Solution Processed Universal Smart Window Coatings
- Utah State University (AMPED) – Dynamic Cell-Level Control For Battery Packs

Once finalized these Impact Sheets will be available on the ARPA-E website at http://arpa-e.energy.gov/.

Additional information and contacts for our Technology-to-Market team can be found on our web page at http://arpa-e.energy.gov/?q=about/arpa-e-team/tech-to-market-team.

Additional information and contacts for our Technology team can be found on our web page at http://arpa-e.energy.gov/?q=about/arpa-e-team/program-directors.

Information on openings for Program Directors (Technology team), Commercialization Advisors (T2M team), and Fellows (Technology Team) can be found on our web page at http://arpa-e.energy.gov/?q=jobs.